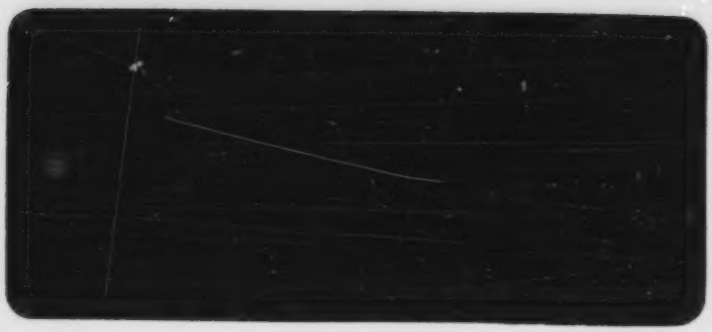

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THE EFFECTIVENESS OF CANADIAN SUPPLEMENTARY CEMENTING MATERIALS IN REDUCING ALKALI-AGGREGATE REACTIVITY

FINAL REPORT

BY

Canada Cement Lafarge Ltd

Dr. H. Chen and R. W. Suderman

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THE EFFECTIVENESS OF CANADIAN SUPPLEMENTARY CEMENTING MATERIALS IN REDUCING ALKALI-AGGREGATE REACTIVITY

ABSTRACT

Eight fly ashes, three slags, two condensed silica fumes, two natural pozzolans, three natural aggregates, and three normal Portland cements were tested for their chemical, mineralogical and physical characteristics. Mortar and concrete prisms were prepared from these mostly Canadian materials to investigate the effectiveness of each supplementary cementing material (SCM) in reducing alkal-silica and alkali-carbonate expansions. For those SCM's which were rated as good inhibitors of the said expansions, their optimum cement replacement levels were also established.

Eleven of these SCM's were found to be effective in reducing alkali-silica expansion, and ten of the same materials were useful for suppressing alkali-carbonate expansion. In the cases of fly ashes, the optimum cement substitution levels are mostly in the 40-50% range. The corresponding values for the slags is 50-65%, for the condensed silica fumes 15% or higher, and finally for the natural pozzolans 20-30%. The silica fume was found to be more effective in combating alkali-silica than in inhibiting alkali-carbonate expansion. The reverse is true for the slags.

Multiple linear regression analyses of the data reveal that the rate of expansion can be related to the properties of SCM such as the sum $SiO_2+Al_2O_3+Fe_2O_3$, -45um content, and total alkali content. Total alkali content of concrete may be used in place of total alkali content of SCM. Based on these properties and the multiple-variable linear equation, one may estimate the cement replacement level required to reduce the rate of mortar or concrete expansion to an acceptable value.

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INTRODUCTION

Some aggregates in hardened concrete have been known to expand due to reaction between certain reactive rock minerals and alkali present in concrete [1-12]. When the expansion of a concrete exceeds a critical level of 0.03 to 0.10%, map pattern cracking occurs [13-14] and causes reduction in its strength, elastic properties and durability [1, 16-17]. The alkali in concrete is normally introduced by cement or aggregate [18-19]. In some cases it may originate from external sources, such as de-icing salts applied on concrete pavement or sea water. It only takes a small quantity of reactive mineral particles, e.g. 3-5% by mass of aggregate, to induce deleterious concrete expansion . There is also a "pessimum" amount of reactive mineral, in relation to alkali content of concrete, to cause a maximum amount of concrete expansion [1,20-23].

Alkali-aggregate reactions (AAR) have been classified into two catagories, namely, alkali-silica reaction and alkali-carbonate reaction. The former may also be subdivided into classical alkali-silica and delayed expanding siliceous reactions [1,24-25]. Information regarding different types of reactive aggregates can be found in a recent book by Dolar-Mantuani [1]. The reactive minerals are often in the forms of glassy, microcrystalline or cryptocrystalline silica or dolomite which are meta-stable. The often cited minerals are opal, tridymite, cristobalite, volcanic glass, chalcedony, feldspars and dolomite. The reactive rock types which bear these minerals are, for examples, shale, sandstone, chert, flint, silicified carbonate, rhyolites, andesites, basalts, quartzite, argillites, siltstones, greywacks, arenites, arkose, slates, phyllites, schists, granites, argillaceous dolomitic or calcitic limestones.

Many cases of alkali-aggregate problems have been identified in central and eastern parts of Canada [1,25-28]. This is because the cements produced in these areas have relatively high alkali contents and many stone quarries produce reactive aggregates. In order to prevent harmful expansion of future concrete structures, there seem to be three options:

(1) to avoid reactive aggregates, (2) to use low alkali cements, and (3) to partially replace cement by SCM. The last option has attracted much attention because of the following reasons:

(1) There is a shortage of good quality aggregates [24].
(2) Low alkali cements are not always available and may not always reduce long term alkali-aggregate expansion [29].

(3) Abundant industrial waste materials, such as fly ash, slag, condensed silica fume, and natural pozzolan are available for use as SCM's in concrete [30-43,50-51].

The objectives of the present study were :

(1) To evaluate the effectiveness of many Canadian fly ashes, slags, condensed silica fumes, and natural pozzolans in reducing alkali-aggregate expansion of concrete and mortar, and

(2) To determine optimum cement replacement level for each SCM in mortar and concrete. One American slag and one American fly ash were also included for comparison purposes.

SURVEY OF PREVIOUS RELEVANT STUDIES

A state-of-art review of fly ash in concrete has been co-authored by Berry and Malhotra in 1986. A section of the book addresses effects of fly ash on AAR in concrete [33]. Based on the existing data, the authors concluded that:

- -Low calcium fly ashes are effective in reducing expansion caused by alkali-silica reaction when used at a replacement level in the range of 25 to 30%.
- -For high calcium fly ashes, the effective replacement levels may be higher than low calcium fly ashes.
- -The mechanism and details of control of expansion caused by alkali-silica reaction are not yet fully understood.
- -The addition of pozzolans is relatively ineffective in reducing alkali-carbonate reaction.

Another review by Hogan [44] in 1985 focused on the effect of blast furnace slag on AAR. The published data have demonstrated that the ability of vitreous slag to reduce AAR was a function of cement replacement level, alkali content, fineness of slag, and chemistry of slag. In general, a replacement level of greater than 50% was required if the binding materials had a combined alkali content of 1.00% as Na_2O equivalent.

The latest review on the effects of slag and fly ash on alkali-silica reaction was authored by Hobbs [45]. He summarized that:

- -The effectiveness of fly ashes and slags in preventing alkali-silica exppansion varied widely.

- In the presence of fly ash and slag, deleterious expansion could occur at lower alkali contents than would be expected if only the alkali contributed by the ordinary Portland cement was important.

- The effectiveness of a fly ash in preventing alkali-silica expansion was inversely related to its total alkali content.

- The partial replacement of a Portland cement by fly ash did not always lead to a reduction in alkali-silica expansion.

- The fly ashes and slags could contribute reactive alkali to concrete.

Hobbs recommended that if fly ash or slag was being considered as a partial replacement for a high alkali cement to reduce the risk of alkali-silica expansion, then either

- the effectiveness of the particular fly ash or slag should be established by a test in which a neutral aggregate is used and in which the concrete is stored moist or wet at 20°C, or

- if tests are not possible, the effective alkali content of the particular fly ash should be taken as one-sixth of its total alkali content and that of the particular slag one-half of its acid-soluble alkali content. The effective alkali contribution from fly ash should then be added to that from the Portland cement and total checked against any specified limit.

Condensed silia fume, being a very active SCM has received much interest in recent years in its ability to control AAR [46-48,50-52]. An international workshop on this material in concrete was held at Montreal, May 1987 [52]. The latest data [48,54,55] suggested that while 8-15% cement replacement by condensed silica fume was adequate to delay short term expansion, a higher level of 20-40% replacement was required to suppress long term reaction. Condensed silica fume was found to be ineffective in reducing expansion due to alkali-carbonate reaction [55-56].

In the 7th International Conference on Alkali-Aggregate Reaction held in Ottawa, 1986, a session was devoted to the effect of pozzolans on alkali-aggregate reaction. Oberholster and Davies [57] reported an extension of their previous study [48]. Large size concrete cubes and beams containing slag, fly ash, calcined shale, and condensed silica fume were exposed outdoors for 4 to 6 years. It was concluded that at a cement replacement level of 50% (mass/mass

or volume/volume), the slag was effective in preventing the deleterious alkali-silica expansion even when the active alkali content of concrete was as high as 4.95 kg/m^3. In a concrete with up to 4.07 kg/m^3 of active alkali content, the fly ash was effective at 15% (mass/mass) replacement. In the case of the condensed silica fume a replacement level of 10% appeared to be effective even when the active alkali content of concrete was as high as 4.99 kg/m^3. However, 15% calcined shale (mass/mass) or 5% condensed silica fume only delayed expansions of the concretes with 4.07 and 3.87% active alkali content, respectively.

A fly ash research group at the University of Calgary has also investigated the effectiveness of several Canadian fly ashes in reducing alkali-silica expansion, using pyrex glass or opal as reactive aggregate [58,59].

Several materials scientists have engaged in basic research on possible mechanisms of reduction of AAR by SCM's. The proposed mechanisms are summarized as follows:

(1) Dilution of alkali hydroxide in cement paste - This is true only if an SCM has a lower alkali content than the cement it replaces and a large proportion of cement is replaced. Very often this mechanism alone could not explain the observed effect [60,62].

(2) Reduction of paste permeability - Pozzolanic or hydraulic reactions of pozzolans and slags increase the proportions of dense calcium silicate and calcium-alumino (or -ferro) hydrates and decrease the proportion of coarser calcium hydroxide in the paste. Consequently, larger capillary pores are converted into interlayer micropores and make the paste less permeable to alkali in pore solution [50-52,61-82,87].

(3) Fixation of alkali in the paste - The calcium silicate hydrate which is formed in the paste of cement and SCM has a much lower Ca/Si ratio than that found in a regular cement paste. This allows the paste to incorporate more alkali in its lattice and thereby reduce alkali in pore solution [50-52,62,69,74,83-92,96].

(4) Formation of non-expansive silica gel - When pore solution contains less alkali because of the use of SCM [89-92, 96], not only that there would be less silica gel formed by reacting with the reactive silica in aggregate, but also the silica gel would contain Ca which renders the gel non-expansive [93-96].

(5) Acceleration or retardation of silica gel formation - One theory is that if alkali in pore solution react quickly with the fine silica of SCM's, silica gel will form mainly

when concrete is still in plastic state and cause little expansion after concrete hardens [94-95]. Another opposite theory is that alkali-silica reaction is delayed due to lower alkali hydroxide concentration in the pore solution. It would take years to detect any expansion.

PROCUREMENT OF MATERIALS

A. Cements

Three commerical Type 10 normal Portland cements were selected. Cement M and cement B have high alkali contents and cement K has a low alkali content. None of the cements contain interground limestone. Cement M was used only in prescreening tests of the aggregates, while cement B was used in combinations with all the SCM's throughout the project. Cement K was simply used as a reference, since it had records of not causing any significant alkali-aggregate expansion.

B. Supplementary Cementing Materials (SCM's)

Eleven Canadian commercial fly ashes and one commercial American fly ash were chosen to represent varying chemical compositions and a wide geographic distribution. However, only eight of these fly ashes were used to make mortar and concrete prisms for expansion measurements. The remaining four fly ashes were simply characterized for possible future studies. The first eight fly ashes were taken from the following geographic locations:

Fly ash L1, N.B.	Fly ash D, N.B.	Fly ash L2, Ont.
Fly ash T, Ont.	Fly ash E, Sask.	Fly ash S, Alta.
Fly ash, Alta.	Fly ash H, Tx., U.S.A.	

In the catagory of slags, two Canadian commercial products and one American commercial product were acquired. These are identified as: Slag S, Slag A1, Slag A2.

Also included in the program were two Canadian natural pozzolans:

Natural pozzolan A Natural pozzolan Q

Two Canadian commercial condensed silica fumes were identified as:

Condensed silica fume S Condensed silica fume C

The geographic locations, where the above SCM's were collected, are shown in Fig. 1.

C. Aggregates

Small samples of four aggregates which have history of causing harmful concrete expansion [1] were initially obtained for prescreening tests. These were rocks from Nairn Falls, Ont., Lady Evelyn Lake, Ont., Pittsburgh quarry near Kingston, Ont., and Trois Rivieres, Que. The first aggregate was later rejected and a few tons of each of the other three aggregates were acquired for mortar and concrete expansion tests. Lady Evelyn Lake and Trois Rivieres rocks were known to be alkali-silica reactive and Pittsburgh rock was considered as alkali-carbonate reactive. Fig. 2 shows the geographic locations from where the aggregates were taken.

TEST PROGRAMS

A. Characterization of Cements

The chemical compositions of cements were determined by X-ray fluorescence (XRF) spectrometry, flame photometry, and Leco furnace/iodometry. Their soluble alkalies were analyzed according to ASTM C114 procedure.

B. Characterization of Supplementary Cementing Materials (SCM's)

All SCM's were subject to the same chemical tests as mentioned above. In addition, carbon content, specific surface area, density, and pozzolanic activity (ASTM C311) were also determined. Qualitative phase analysis was performed by powder X-ray diffractometry (XRD). Sedigraph 5000 Particle Size Analyzer was employed to determine granulometry. ASTM C441 procedure was also followed to assess reduction in expansion due to alkali-pyrex glass reaction.

C. Aggregates

For prescreening, ASTM C289 and C227 methods and PCA osmotic cell test were performed on the following small-size samples: Nairn Falls #1 (bed rock), Nairn Falls #2 (outcrop), Nairn Falls #3 (outcrop), Lady Evelyn Lake, Trois Rivieres, Pittsburgh #1, and Pittsburgh #2 (face). Both high alkali cement M and low alkali cement K, but not cement b, were used in C227 tests.

After it was decided to use Lady Evelyn Lake, Trois Rivieres, and Pittsburgh rocks for the entire study, more complete characterizations of these rocks were carried out by x-ray diffraction, microscopy, chemical analyses (XRF, flame emission, Leco Furnace and iodometric titration), scanning electron microscope and microprobe analysis.

D. ASTM C227 Mortar Bar Expansion

This standard testing procedure was essentially adhered to except that a constant water to total binding maerial ratio, W/(C+SCM), of 0.48 was maitained in all mixtures in order to avoid possible influence of this parameter on alkali-aggregate expansion. For a few mixtures containing condensed silica fume or natural pozzolan, it became necessary to add a naphthalene-based-superplasticizer to make the mortars workable.

Since this test may not be suitable for alkali-carbonate reaction, Pittsburgh rock was excluded from this part of the program. For the other two aggregates, each was tested with high alkali cement B, at the following replacement levels by SCM's:

Fly ash - 0, 20, 30, 40, and 50% (except that fly ash F at 20, 30, 40% and fly ah H at 30, 40, 50%)

Slag - 35, 50, and 65% (except slag A2 at 20, 45, 60%)

Condensed silica fume - 5, 10, and 15%

Natural pozzolan - 10, 20, and 30%

For four particular mixtures containg Lady Evelyn Lake aggregate and fly ash L1 (0, 20, 30, 40%), the tests were repeated with higher cement total alkali of 1.25% eq. Na_2O by adding NaOH to the mixtures. A reference mixture containing low alkali cement K only was also prepared.

Two mortar bars were prepared for each mixture and stored in standard tin or stainless steel cans. Wicks were used in the containers to improve uniformity of at least 95% R.H. at 38°C. The expansions were measured at 14- and 28-day, and subsequently at 2, 3, 4, 6, 9, 12, 18 months and 2, 3, 4, 5 years.

E. CSA A23.2-14A Concrete Prism Expansion

This standard testing method was followed except that the constant slump was changed to constant water to total

cementitious material ratio, W/(C+SCM), for a given aggregate, for the same reason as mentioned in the previous section. All of the three aggregates were used. The proper W/(C+SCM) ratio to be maintained for the concrete mixtures containing the same aggregate was that required to yield a 80mm slump for the control mixture. The values were 0.53, 0.52, and 0.58 for Lady Evelyn Lake, Trois Rivieres, and Pittsburgh aggregates, respectively. A naphthalene-based superplasticizer was required in a few cases to have workable concrete. No air entraining agent was added to any concrete mixtures. Suitable quantity of each concrete mixture was made so that one could make (1) three concrete prisms for indoor exposure and two prisms for outdoor exposure, and (2) three 102 mm by 203 mm cylinders. Two cylinders were tested for 28-day compressive strength and one cylinder for 84-day strength. The expansions of the prisms were measured at the same ages as the mortars.

The purpose of the outdoor exposure is to monitor the expansion of the real concrete and correlate it to the expansion of the lab-cured concrete. Unfortunately, many measurements could not be carried out when the specimens were frozen to the ground. It is also feared that the expansions due to freeze-thaw action and alkali-aggregate reaction would not be distinguished. Therefore, the incomplete data of outdoor specimens are not included in the report.

The SCM's were used at the following cement replacement levels:

Fly ash - 0, 20, 30, 40, and 50% (except that fly ash F at 20, 30, 40% and fly ash H at 30, 40, 50%. These two fly ashes were not tested with Pittsburgh aggregate)

Slag - 35, 50, and 65% (except slag A2 at 20, 45, 60%)

Condensed silica fume - 5, 10, and 15%

Natural pozzolan - 10, 20, and 30%

Fly ash L1 was also tested with Trois Rivieres aggregate in high cement factor (550 kg/m^3) mixtures at the replacement levels of 0, 20, 30, and 40%.

After the short term expansion data were available, it was apparent that all concretes containing Lady Evelyn Lake or Trois Rivieres aggregate were slow expanding. Some tests were, therefore, repeated with total cement alkali adjusted upward to 1.14 or 1.25%. These include control concrete mixtures of both aggregates, and the Trois Rivieres concrete containing fly ash L1 at 30, 40, 50% or slag S at 35, 50, 65% levels.

F. Methanol-Water Exchange

Methanol-water exchange tests [97-98] of mortars were included in the early stage of the project with the objective of determining if porosity of the paste in a mortar could be decreased by the use of SCM and thereby reduces alkali-aggregate reaction. A few mortars were prepared independently from the other mortar bars and concrete prisms. This part of test program was later discontinued.

RESULTS

A. Characteristics of Materials

1. Cement Compositions

The chemical compositions of the three cements are given in Table I. Also shown in the table are Bogue potential compounds and sulfates calculated from the oxide values.

2. Properties of Supplementary Cementing Materials

The chemical analyses and physical properties of the eight fly ashes are compiled in Table II. The similar data of the slags, the condensed silica fumes, and the natural pozzolans are shown in Table III.

The crystalline phases identified by XRD and the 2 theta peak values of the broad XRD peak, indicative of varying glassy phase composition, particularly the %CaO in the glassy phase [99], are included in Table IV.

The curves obtained by Sedigraph Particle Size Analyzer are displayed in Figs. 3-17.

3. Characteristics of Aggregates

The results of prescreening tests on aggregate samples by ASTM C289 chemical method and Portland Cement Association's osmotic cell method are listed in Table V. Only Lady Evelyn Lake aggregate was rated by the C289 test as deleterious. On the other hand, based on the osmotic cell data, D. Stark of PCA considered Nairn Falls #1 (bedrock), Lady Evelyn Lake, and Pittsburgh #1 rocks to be reactive and the other rocks to be innocuous.

The C227 mortar bar expansion data of the samples for prescreening can be found in Table VI and compared in Figs. 18-20. If based on the criteria of 0.05% at 3-month and 0.10% at 6-month, only Lady Evelyn Lake aggregate can be rated as deleterios and the other rock samples to be nonreactive. However, Nairn Falls #1 and #2, and Trois Rivieres rocks exhibited definite trends of expansion. Even Pittsburgh #1 and #2 rocks in combination with high alkali or low alkali cement were surely expanding at lower rates, despite that this test method is generally considered to be unsuitable for alkali-carbonate reaction.

The Nairn Falls aggregate is a dark-grey, massive, and fined-grained sedimentary silicate rock. It is classified as argillaceous arkose, or subarkose argillite, or arenite. Its major mineralogical constituents are muscovite, quartz, plagioclase feldspar. There is also ilmenite as a minor mineral.

The Lady Evelyn Lake rock is a well indurated, dark-grey, varved argillite, which is weakly metamorphosed. It consists of alternate argillaceous and silty beds where argillaceous beds are more important. Some calcite and chlorite veins are present. Its major minerals are quartz, potassium feldspar, plagioclase feldspar, illite, chlorite, minor calcite, pyrite, and charcopyrite. The results of XRF anaysis are as follows:

SiO_2 58.2, Al_2O_3 18.8, $FeO+Fe_2O_3$ 9.9, MgO 2.9, Na_2O 1.5, K_2O 3.2, CaO 1.1, TiO_2 0.7, LOI 5.4%.

Immersion of the Lady Evelyn Lake rock particles in a 2N KOH or NaOH solution at 37°C caused formation of white silica gel on the surfaces of the particles. Pyrite also appeared to be rusted. These reactions were evident only after three weeks of immersion and progressed rapidly afterward. Dolar-Mantuani [100] and St. John [101] also observed silica gel in the concrete samples of Lady Evelyn dams. These authors concluded that chert (5-10%) and green argillite were responsible for the reaction, but the reactive mineral was not identified.

The Trois Rivieres aggregate is a fine-grained limestone with zones rich in calcitic fossils and sponge-like siliceous fossils. The limestone has 95% calcite and 4% of materials (e.g. illite, quartz, feldspar, chlorite, dolomite, and pyrite) which are insoluble in hydrochloric acid. Its chemical composition is :

SiO_2 2.7, Al_2O_3 0.7, $FeO+Fe_2O_3$ 0.5, MgO 0.8, Na_2O 0.04, K_2O 0.1, CaO 51.4, TiO_2 0.12, LOI 42.2%.

This aggregate reacted very slowly in a 2N NaOH or KOH solution. After ten weeks of immersion, the only product observed was white deposite of $Ca(OH)_2$ which was formed by the attack of alkali on calcitic fossils. There was no evidence of gel formation.

The Pittsburgh aggregate is also a fine-grained, and slightly fossilized argillaceous dolomitic limestone. The minerals present are 55% calcite, 27% dolomite, quartz, feldspar, illite, chlorite, and pyrite. Its oxide composition is:

SiO_2 10.6, Al_2O_3 3.1, $FeO+Fe_2O_3$ 0.9, MgO 4.1, Na_2O 0.04, K_2O 1.06, CaO 40.6, TiO_2 0.1, LOI 37.8%.

After three weeks of immersion of this rock in a 2N KOH or NaOH solution, the alkali attacked calcite to form $Ca(OH)_2$, and after six weeks, the presence of $Mg(OH)_2$, Na_2CO_3, and K_2CO_3 was evident under a scanning electron microscope (SEM) and electron microprobe analysis. These compounds were the products of dedolomization process [102]:

$$CaMg(OH)_2 + 2MOH \rightarrow Mg(OH)_2 + M_2CO_3 + CaCO_3$$

$$M_2CO_3 + Ca(OH)_2 \rightarrow 2MOH + CaCO_3, \quad \text{where M=K or Na.}$$

The above petrographic analysis and alkaline immersion study of the three aggregates were carried out by B. Durand.

B. Slumps and Compressive Strengths of Concrete

The slumps of concrete containing Lady Evelyn Lake aggregate were plotted in Figs. 21-22 for each SCM as a function of cement replacement level. The similar data for the concrete of Trois Rivieres aggregate were illustrated in Figs. 23-24, and the results of concrete containing Pittsburgh aggregate were depicted in Figs. 25-26.

The 28-day and the 84-day compressive strengths of the concrete were compared in Figs. 27-34 for the Lady Evelyn Lake aggregate, in Figs. 35-42 for the Trois Rivieres aggregate, and in Figs. 43-50 for the Pittsburgh aggregate.

The values of slumps and compressive strengths were collected in Table VII for the Lady Evelyn Lake aggregate, in Table VIII for the Trois Rivieres aggregate, and in Table IX for the Pittsburgh aggregate.

C. Expansion Data

1. ASTM C441 Tests - Reductions of Mortar Bar Expansions by Mineral Admixtures

The tests were carried out according to C441 specification. Pyrex glass was used as a reactive aggregate and the cement replacement leveel was fixed at 25% by volume of cement. The W/(C+SCM) ratio was varied in order to maintain a flow of 100-115%. The data obtained were given in Table X. The amount of $Ca(OH)_2$ present in the mortar bars were also included in this table. The expansions were only monitored to 56-day and are illustrated in Figs. 51a and 51b.

Fly ash H and slag A2 were not included, since these two SCM's were added later to the program. It should also be mentioned that the sample of fly ash F used in this part of the program was not the same as that used in C227 and CSA 23.2-14A tests. The former was coarser than the latter and was also different in chemical composition.

2. Mortar Bar Expansions by ASTM C227

The expansion data and soluble alkali contents of mortar bars containing Lady Evelyn Lake aggregate were presented in Table XI and illustrated in Figs. 52-99. For each SCM, the expansion was plotted against time in month, against time in square root$_3$ of day, and versus soluble alkali content of mortar in kg/m^3. Also shown in each figure are the expansion curves of the control mortars containg high alkali or low alkali cement.

The mortar bar expansions of the Trois Rivieres aggregate were very low. Therefore, they were not presented in graphic forms and only collected in Table XII.

3. Concrete Prism Expansions by CSA 23.2-14A

The expansion results and soluble alkali contents of the concretes with the Pittsburgh aggregate were collected in Table XIII and Figs. 100-139. These curves were plotted in the same manners as in the cases of C227 mortar bar expansions. The concrete prisms of the Lady Evelyn Lake and the Trois Rivieres aggregates have not expanded appreciably. Their data were presented in Table XIV and Table XV, respectively.

D. Methanol-Water Exchange

The results of this test were presented graphically in Appendix A. The % weight loss of an immersed mortar, measured 3mmx40mmx60mm in size, was plotted as a function of square root of minutes. At the time this part of the program was suspended, the following mortars containing the Lady Evelyn Lake aggregate had been tested:

Fly ash L1 at 15%, 25%, 35% cement replacement levels;
Fly ash T at 15%, 25%, 35% cement replacement levels;
Condensed silica fume S at 7, 15, 25% replaceement levels;
Control with the high alkali cement B.

DISCUSSION

A. Effect of Supplementary Cementing Materials on Slumps and Compressive Strengths of Concrete

In general, partial replacement of the cement by the fly ashes have caused substantial increases in concrete slump. The exception was fly ash L2 in the concrete of Lady Evelyn Lake aggregate and in the concrete of Pittsburgh aggregate. The effect has been commonly attributed to the spherical particle shape of the fly ashes until recently. Helmuth [104] proposed an alternative hypothesis which stated that the adsorption of very fine fly ash particles on portions of the cement particles is responsible. The effect on slump due to the other SCM's was inconsistent.

The compressive strengths of various concrete mixtures were very significantly affected by the incorporation of the SCM's. The effect varied with the SCM and was also somewhat dependent upon the aggregates. It was also possible that some of the 84-day strengths of the concrete showing excessive expansions might have been affected by microcracking.

Fly ashes L1, D, S and L2 showed adverse effect on 28-day concrete strength. The influence was most pronounced at the 50% replacement level, the level found to be most effective in reducing alkali-aggregate expansion. The effect was not as severe at 84-day. In the cases of fly ashes F, T, E, and H, the concrete strengths were either very close to or better than those of the control. These latter fly ashes had higher CaO and alkali contents and were not effective inhibitors of alkali-aggregate expansion.

The replacement of the cement B by condensed silica fume S or C resulted in substantial improvement in 28-day

and 84-day concrete strengths. However, the 5-15% cement replacements were just high enough to reduce alkali-silica expansion but not sufficient to inhibit alkali-carbonate expansion.

Among the three slags studied, the slag A1 was consistently the best strength performer in all concrete mixtures. At up to 50% cement replacements, it produced the strengths which were higher than or close to the controls (except 84-day of the Trois Rivieres aggregate). At 65% replacement both 28- and 84-day strengths were somewhat degraded. The slag A2 was quite similar to the slag A1 in strength properties, in some cases even better. On the other hand, the use of the slag S often resulted in appreciable reduction in strength.

Partial substitution of the cement B by the natural pozzolan A in general greatly improved concrete strength. The opposite was true for the natural pozzolan Q.

B. Effectiveness of Mineral Admixtures in Preventing Excessive Expansion due to Alkali-Aggregate Reaction by ASTM C441 Method

In ASTM C441, it is specified that a mineral which is acceptable in reducing the said expansion must be capable of decreasing the control expansion at 14-day by at least 75% and the expansion should also be smaller than 0.02%.

Based on the above criteria, only three SCM's, i.e. the two condensed silica fumes and natural pozzolan A, were acceptable. The mortars of these SCM's contained the lowest amounts of $Ca(OH)_2$, indicating more complete pozzolanic reaction. Fly ash T, slag S, and natural pozzolan Q were close to being acceptable. It should be pointed out, however, that the replacement level of 25% by absolute volume is not necessarily at optimum. Pyrex glass, although extremely reactive, is very different from the aggregates which would normally be used in concrete. In addition, the C441 test was mainly designed for alkali-silica reaction; it may not be suitable for alkali-carbonate reaction.

C. Other Criteria for Evaluating the Effectiveness of Supplementary Cementing Materials on Alkali-Aggregate Reaction

Various safe expansion limits on AAR are specified in different standard testing methods. These have been compared by Grattan-Bellew [14,24] and Rossouw and Kruger [105]. As

mentioned previously, an expansion of 0.03-0.10% is generally considered to be the critical level for the commencement of cracking in mortar or concrete. This level of expansion is also often associated with a critical level of soluble alkali per unit volume of mortar or concrete [20,21,45,60]. The safe expansion limits in the range of 0.03-0.10% at any age are considered to be realistic for mortar and concrete prisms, except in the cases of alkali-carbonate reaction [13,14,24]. A safe expansion limit in a lower range of 0.015-0.025% at three to twelve months is considered to be more appropriate for concrete expansion due to alkali-carbonate reaction [13].

Grattan-Bellew [14,24] has also proposed new criteria based on rates of expansion to differentiate deleterious and innocuous expansions caused by different types of aggregates. The approximate rates of expansion proposed by the author to reject expansive aggregates were: (1) greater or equal 0.007 for alkali silica and late expansive siliceous aggregates at any age, both for mortar and concrete; (2) greater or equal to 0.004 at any age for carbonate reactive aggregate in concrete.

In the present study, an expansion curve plotted versus square root of time usually exhibits a linear section corresponding to the active expansion period of mortar or concrete. However, in some cases, it was difficult to define such a linear portion of the curve. Therefore, we have determined the slope of expansion whenever it was possible. These values were compiled in Table XVI for mortars and in Table XVII for concrete prisms.

In addition to the safe limits and rates of expansion as discussed above, the expansion of control mortar or concrete containing the low alkali cement K may well serve as references for judging the effectiveness of SCM's in reducing AAR expansion, since this particular cement effectively prevented expansion rather than delaying it.

D. Effect of Supplementary Cementing Materials on Alkali-Silica Reaction

Up to the age of two years, the C227 mortar bars which had showed significant expansions were only those of the Lady Evelyn Lake aggregate. The mortar bars of the Trois Rivieres aggregate had been very slow expanding. The fact that this aggregate had only 4% of acid insoluble materials led one to think that there was not enough reactive mineral in this rock. The reactive Trois Rivieres rock had been reported elsewhere to contain as much as 12% insoluble [106].

It was noted that despite the strong reactivity of LEL rock in the mortars, the corresponding CSA concrete prisms have exhibited very little expansions so far. The possible explanations are: (1) The total alkali contents of the concrete prisms were much lower than the corresponding mortars, being only 35% of the mortar values. (2) Total alkali to reactive mineral ratio might be too far from the pessimum. (3) The particle sizes of aggregate in concretes were much larger than those in mortar. (4) The W/(C+SCM) ratio of the concrete was higher than the mortar. (5) It is possible that the relative humidy of the curing room was lower than expected. It should be mentioned, however, that Grattan-Bellew has reported that, for the same aggregate, concrete expansion was in general greater than mortar expansion [14,24].

The present discussion on alkali-silica reaction will focus on the effect of each SCM on the expansions of the mortars containing Lady Evelyn Lake aggregate. Later in section VI-F-1, the data of the entire series of mortars will be discussed in the light of multiple-linear-regression analysis.

1. Control Mortars (Tables XI, XVI Figs.52-53)

A total of 12 mortar bars of the high alkali cement B were prepared at different times. The average expansion data of the first 10 bars were used to plot the control expansion curve in Figs.52-99. The expansion at 3-month and 6-month were below the C227 safe limits of 0.05 and 0.10%. Between 6 and 24 months, there had been very little expansion (see Fig 52). The rate of expansion between 1 and 6 months was 0.006, just below the limit of 0.007. When used with the high alkali cement B the Lady Evelyn Lake aggregate was, therefore, innocuous. Previously the same aggregate was rated as deleterious when tested with the high alkali cement M (Table VI and Fig. 19). The difference may be attributed to the lower total and soluble alkalies in the cement B (Table I). The control mortar had a soluble alkali content of 5.36 kg eq.Na_2O/m^3.

The control mortar containing the low alkali cement K expanded at the rate of 0.002 between 1 and 4 months and levelled off thereafter (Table XI). The Lady Evelyn Lake aggregate was clearly safe to use in this mortar. The soluble alkali content of this mortar was 1.1 kg eq.Na_2O/m^3.

2. Fly Ash L1 (Tables XI, XVI and Figs.52-57)

At the 10% cement replacement level, this fly ash delayed mortar expansion in the first 5 months. After 6

months, the expansion overtook that of the high alkali control mortar. Neverthless, it was still within the safe limit of 0.10%. On the other hand, its rate of expansion between 2 and 9 months was 0.008, slightly exceeding the acceptable criterion. At the higher replacement rates of 20-50%, this fly ash effectively suppressed the mortar expansion, most notably at the 40 and 50% substitution levels the expansions were less than the low alkali control mortar at any age (Figs. 52-54). A soluble alkali content of 4.4 kg eq.Na_2O/m^3 of the mortar at the 20% cement replacement appeared to be the limit below which the expansion could be prevented over a long term (Fig. 54). Apparently at the 10% cement replacement level, the reactive mineral to alkali ratio was at the pessimum.

The addition of NaOH to raise the total alkali to 1.25% by mass of cement has increased expansions at all cement substitution levels and all ages (Table XI and Figs.55-56). In order to offset the effect of NaOH, a corresponding increase of 10-20% fly ash was required. After one year, the expansions of the mortars, with 20-40% of its cement replaced by the fly ash, were still below 0.10% and expanding at the rates slower than 0.007. However, one has to see the longer terms data to acertain if these mortars continue to expand under safe margins. No pessimum was observed in this series of tests, because no 10% replacement level was tested.

3. Fly Ash D (Tables XI,XVI and Figs. 58-60)

The mortars of this series showed a pessimum cement replacement level at 10%. At this level, the rate of expansion was 0.016 compared to 0.000 of the high alkali control mortar. The expansion also exceeded 0.10% at 6-month. On the other hand, at the 20-50% levels, the aggregate could be rated as innocuous by all criteria. The substitution of 40 or 50% of the cement by this fly ash was as effective as the use of low alkali cement K. The critical soluble alkali content in the mortar was 4.3%, which was almost the same as that of the mortar containing the fly ash L1.

4. Fly Ash L2 (Tables XI, XVI, and Figs.61-63)

Again we observed a pessimum cement replacement level of 10% in this series of mortars. The aggregate was clearly deleterious when this amount of fly ash was introduced into the mortar. Its magnitude of expansion surpassed those of the corresponding mortars of the fly ashes L1 and D. By increasing the fly ash dosages to between 20 and 50%, the harmful consequences were virtually prevented. The safe limit of soluble alkali was 4.4 kg eq.Na_2O/m^3 of the mortar, which

agreed well with the previous two fly ashes. In order to achieve the same low expansion as the low alkali control mortar, the dosage of the fly ash needed would be between 30% and 50%, again very similar to the fly ashes L1 and D.

5. Fly Ash S (Tables XI, XVI, and Figs. 64-66)

The expanding characteristics of this series of mortars were very similar to those of the fly ash L2 series. The comments made in the last section are equally applicable to this series.

6. Fly Ash T (Tables XI, XVI, and Figs. 67-69)

This fly ash was not effective in reducing long term mortar bar expansions, despite that some beneficial results were observed in the early stages when more than 20% of the cement B was replaced. At the dosage rates of 40 and 50%, the expansions after one year exceeded that of the high alkali cement control mortar, but still stayed within the safe rate and limit of expansion. A higher than 50% cement replacement may be required to actually reduce the control mortar expansion over long term. The pessimum was found at the 10% level.

In contrast to the mortars of the other fly ashes, the expansions of this series of mortar were inversely proportional to the soluble alkali content of the mortars at all ages (Fig.69). This phenomenon could be attributed to the fact that the soluble alkali of the fly ash was higher than that of the cement. The same was also noticed in the series of mortars containing the condensed silica fume C.

It should be noted that the fly ash T is very high in specific surface area, Na_2O, and SO_3 (Table II). It is not considered as typical of the more recent production. The private communications with Hooton, Elmhirst, and Carrete led to the conclusion that the present sample could have been taken from the last section of the electrostatic precipitator before the commercial development of this fly ash was begun.

7. Fly Ash E (Tables XI, XVI, and Figs. 70-71)

The pessimum cement replacement level of this series was either 10% or 20%, depending on whether it was before or after 21 months. The rates of mortar bar expansion at all cement replacement levels had exceeded 0.007 and the trend of continuing expansion over long term was evident, albeit

the bars with less than 4.55 kg soluble eq.Na_2O/m^3 satisfied the C227 limits at 3 and 6 months. Undoubtedly, this fly ash could only increase the alkali-silica expansion of the Lady Evelyn Lake aggregate. It was the least effective among the eight fly ashes included in this study.

8. Fly Ash F (Tables XI, XVI, and Figs. 73-75)

When compared with the other high alkali fly ashes E and T, this fly ash appeared to be quite good in reducing mortar expansion up to the age of one year. The minimum fly ash dosage required was about 30% substitution for cement, or equivalent to 3.9 kg soluble eq.Na_2O/m^3 of mortar. The pessimum could be well below 20% level. It should be noted that the expansions are still continuing.

9. Fly Ash H (Tables XI, XVI, and Figs. 76-78)

In the first six months, the expansions of the mortars containing this fly ash were less than that of the high alkali control mortar. Unfortunately from then on, these mortars continued to expand in contrast to the control mortar. Evidently, at the cement replacement levels of 30-50%, this fly ash could only retard early stage expansion and enhance longer term expansion of the mortar. The effect of this only class C fly ash we have studied was very similar to that of fly ash T, at least in the first year of observation.

10. Slag S (Tables XI, XVI, Figs. 79-81)

The replacement of the cement B by 50 and 65% of this slag had successfully suppressed mortar bar expansion after two months. The expansion seemed to have levelled off after six months and remained very low up to two years. However, the pessimum replacement level was near 35%. At this level, the fly ash reduced the expansion before one year and increased the expansion thereafter.

11. Slag A1 (Tables XI, XVI, Figs. 82-84)

The influence of this slag on mortar expansion was very similar to the slag S. The pessimum cement replacement was near 35% and the optimum replacement was approximately 65%.

12. Slag A2 (Tables XI, XVI, Figs. 86-88)

The slag A2 appeared to be somewhat more effective than the other two slags in reducing mortar bar expansion when used at the cement substitution rates of 45 and 60%. At 60% level, the expansion was nearly reduced to that of low alkali control mortar. On the contrary, at the pessimum level of 20%, it drastically enhanced the expansion.

Overall, all the three slags were effective expansion reducers. However the required optimum dosages were much higher than those of the good fly ashes discussed above, probably due to the lower sum $SiO_2+Al_2O_3+Fe_2O_3$. This was somewhat compensated by the lower total alkali.

13. Condensed Silica Fume S (Tables XI, XVI and Figs. 88-90)

The incorporation of the condensed silica fume S at 5% level only slowed down the expansion in the first seven months. After that period the expansion overtook that of the high alkali control mortar. This is another example that despite the expansions at three and six months remained within the limits of C227, the mortar could still expand rapidly and exceeded 0.10% safe limit at a later age. In this case, the rate of expansion of 0.008 seems to be a better indicator of this aggregate being deleterious. As the replacement was increased to 10 and 15%, the expansion was greatly retarded. The mortar of the cement B with 15% of this condensed silica fume appeared to perform better than that of the low alkali cement K up to two years, but it was still expanding. Regenerationn or slow release of alkali with time could be the reason [56].

14. Condensed Silica Fume C (Tables XI, XVI, and Figs. 91-93)

This condensed silica fume seemed to be less effective than the condensed silica fume S in suppressing alkali-silica expansion. This could be attributed to the lower $SiO_2+Al_2O_3+Fe_2O_3$, the lower minus 45 micron content, and the higher total alkalies. At the beginning of this project, a low silica material was intentionally used to compare with the high silica materials. It should be pointed out that both grades of silica fume are available from the same suppliers.

At the 5% and the 10% cement replacements, this SCM simply retarded the expansion in the first few months. The long term expansions of the mortars were actually greater than those of the control. At the 15% replacement, the mortar only expanded 0.047% which was less than the control. However, it may surpass the control over longer terms.

Like the fly ash T, the condensed silica fume C has relatively high soluble alkali. However, it did not seem to have an appreciable adverse effect on the mortar expansion.

Overall, this condensed silica fume can be considered as good as a good fly ash in its ability to retard or reduce alkali-silica expansion.

15. Natural Pozzolan Q (Tables XI, XVI, and Figs.94-96)

Natural pozzolan Q has a pessimum replacement level near 10%. It required at least 30% cement replacement in order to reduce the expansion of the control mortar, a performance which was below that of a good fly ash. It should be noted that this material has a very high total alkali.

16. Natural Pozzolan A (Tables XI, XVI, and Figs 97-99)

At the 30% cement replacement, this SCM was most effective in controlling the mortar expansion. Before 24 months one only observed very small mortar shrinkage instead of expansion. This performance was better than all the SCM's studied in this project. This material had relatively high SiO_2, high specific surface area, and extremely low total alkali.

E. Effect of Supplementary Cementing Materials on Alkali-Carbonate Reaction

Up to two years, the CSA concrete prisms which had expanded appreciably were only those of Pittsburgh aggregate. The concretes of other two aggregates had failed to show any significant expansions. Most surprising was the fact that even the Lady Evelyn Lake aggregate which had been expansive in mortar had not been reactive in concretes at all. This was previously discussed in section VI-D. Our present discussion will focus on the effect of each SCM on alkali-carbonate expansion of the concretes containing Pittsburgh aggregate. In addition, multiple-linear-regression analysis which was based on the data of all concretes of this aggregate and all SCM's will be presented in section VI-F-2.

One common feature which was observed for most of the Pittsburgh concretes containg SCM's was that the pessimum replacement level, which was so often apparent in the Lady Evelyn Lake mortars, was no longer observed.

1. Control Concretes (Tables XIII, XVII and Figs. 100-101)

The control concrete of Pittsburgh aggregate and the high alkali cement B has exhibited a steady expanding characteristic up to two years and is still expanding. By all criteria Pittsburgh aggregate in concrete was very reactive toward cement alkali. The rate of expansion of 0.009 was considered fast. Furthermore, its expansions at 3-, 6-, and 12-month were 0.068%, 0.094%, and 0.115%, respectively, far above the acceptable safe limits.

On the other hand, the control concrete containing the same aggregate and the low alkali cement K did not expand perceptibly until two years. This low alkali control concrete could serve as an additional reference for evaluating the effectiveness of each SCM in reducing alkali-carbonate expansion.

2. Fly Ash L1 (Tables XIII, XVII, and Figs.100-102)

When the high alkali cement B in concrete was progressively replaced by this fly ash, both the rate of expansion and the expansion had been gradually depressed. In order to achieve less than 0.015% expansion, 50% cement replacement seemed to be required. Such a concrete had a total alkali of 5.4 kg eq.Na_2O/m^3 or a soluble alkali of 1.1 kg eq.Na_2O/m^3.

3. Fly Ash D (Tables XIII, XVII, and Figs. 103-105)

By comparison with the fly ash L1, this fly ash was significantly more useful in combating alkali-carbonate expansion. The reason of being more effective appeared to be mainly due to the lower total alkali content of the fly ash. At the 40 to 50% replacements, the blended cement virtually behaved like the low alkali cement K.

4. Fly Ash L2 (Tables XIII, XVII, and Figs. 106-108)

The performance of this fly ash in concrete in the first two years was quite similar to the fly ash L1. The optimum substitution rate for the high alkali cement B was 50%.

5. Fly Ash S (Tables XIII, XVII, and Figs. 109-111)

This fly ash also behaved similarly to the fly ash L1. At the 50% blending ratio to the high alkali cement B, the concrete expansion was reduced to slightly lower than that of the low alkali control concrete.

6. Fly Ash T (Tables XIII, XVII, and Figs.112-114)

This high alkali fly ash only enhanced alkali-carbonate expansion of concrete with a pessimum in the range of 20-40%. Future tests at higher than 50% cement replacement levels may be warranted, since the concrete strenth performance of this fly ash was not adversely affected by high cement replacements (see Figs. 28, 32, 36, 40, 44, 48).

7. Fly Ash E (Tables XIII, XVII, and Figs.115-117)

This high alkali fly ash had a pessimum replacement level in the 20-30% range. Like the fly ash T, the expansions and the rates of expansion at all the replacement levels were greater than those of the high alkali control. For the same reason, more tests at higher than 50% replacement should be conducted in the future.

8. Slag S (Tables XIII, XVII, and Figs.118-120)

The expansion of the concrete was drastically reduced when 35-65% of the high alkali cement B was replaced by this slag. The optimum requirement of the slag was about 50%.

9. Slag A1 (Tables XIII, XVII, and Figs.121-123)

This slag was as effective as the slag S in reducing the expansion. The optimum cement replacement level was 65%.

10. Slag A2 (Tables XIII, XVII, and Figs.124-126)

This slag also showed the same beneficial effect as the slag A1. The optimum level of cement replacement was near 60%.

11. Condensed Silica Fume S (Tables XIII, XVII, Figs. 127-129)

In contrast to its effect on alkali-silica mortar expansion, this condensed silica fume was apparently only as effective as a good fly ash in reducing alkali-carbonate concrete expansion. It may take much higher than 15% cement replacement in order to match the expansion of the low alkali control concrete.

12. Condensed Silica Fume C (Tables XIII, XVII, and Figs.130-132)

The performance of this low silica condensed silica fume was very poor. The substitution of this SCM for the cement B initially retarded the concrete expansion. But after 6 months, the expansion overtook that of the control, the higher the replacement the worse it became.

13. Natural Pozzolan Q (Tables XIII, XVII, and Figs. 133-135)

The use of this natural pozzolan substantially reduced the concrete expansions at all ages. However, much higher than 30% cement replacement level would be required to reach the performance equivalent to that of the low alkali control concrete.

14. Natural Pozzolan A (Tables XIII, XVII, and Figs. 136-138)

Compared with natural pozzolan Q, natural pozzolan A was a much better inhibitor for alkali-carbonate expansion. A blend of 70% high alkali cement B and 30% natural pozzolan A was as good as the low alkali cement K in combating concrete expansion. The optimum dosage seemed to be 20-30%.

F. Correlations of Rate of Expansion and Properties of Supplementary Cementing Materials, Mortar, and Concrete

Multiple-linear-regression analysis of the form,

$$X_1 = B_1 + B_2X_2 + B_3X_3 + B_4X_4 + \ldots + B_nX_n,$$

was carried out separately for the mortars of the Lady Evelyn Lake aggregate and the concretes of Pittsburgh aggregate. The objective was to establish correlations between rate of expansion (a dependent variable X_1), and the other variables as listed below:

X_2 = cement replacement in mortar or concrete, in %
X_3 = (SiO_2 + Al_2O_3 + Fe_2O_3) of a SCM, in %
X_4 = Blaine of an SCM, in cm^2/g
X_5 = minus 45um of an SCM, in %
X_6 = pozzolanic activity with lime of an SCM, in MPa
X_7 = pozzolanic activity with cement of an SCM, in %
X_8 = combined soluble eq. Na_2O of a cement & an SCM, in kg/m^3
X_9 = combined total eq. Na_2O of a cement & an SCM, in kg/m^3
X_{10} = total eq. Na_2O of an SCM, in %

Some of the independent variables are actually related to each other as indicated later by single correlation matrix. This will be taken into account in the interpretation of multiple correlations.

1. Mortars of Lady Evelyn Lake Aggregate (data in Table XVIII)

Since it was not always possible to determine a rate of expansion, we used only 42 of the 62 sets of observations in the regression analysis. Some of the variables either did not have enough values to cover a wide range or the values did not normally distribute over an entire range. Despite such shortcomings, the regression exercise was still carried out to obtain quantitative expressions of the relationships between rate of expansion and other properties of mortar and SCM's.

Multiple-linear-regression was run for the ten variables. A microcomputer performed the statistical analysis for every possible combination of 2, or 3, or 4, or 5, or 6, or 7, or 8, or 9, or 10 variables. The usual F-test [107] revealed that many possible combinations of the independent variables produced highly significant correlations. The values of the following statistical criteria were used to judge a degree of correlation:

R - coefficient of overall correlation
F - value of F-distribution
P - probability of a larger value than F by chance; a probability of smaller than 0.05 meams very significant correlation, of smaller than 0.01 means highly significant.
Beta - Beta coefficient of the independent variable i; the larger the value the greater the contribution of this variable to the dependent variable
B - partial correlation coefficient of the independent variable i, i.e. the coefficient of a regression equation.

The F-test of single-independent-variable regression indicates that X_1 (rate of expansion) is most significantly related to X_2 (cement replacement level by an SCM), with X_{10} (total eq.Na_2O of SCM in %) ranked in the second. The other independent variables are individually insignificant. The following single-correlation matrix shows some correlations between the independent variables.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	
X_1	1.00	-.51	-.11	-.18	-.19	.05	.08	.12	.01	.40	X_1
X_2		1.00	-.39	-.40	-.15	-.22	.05	.01	.59	.24	X_2
X_3			1.00	.30	-.03	-.12	-.25	-.11	-.19	-.20	X_3
X_4				1.00	.52	.47	.12	.07	-.35	-.37	X_4
X_5					1.00	.59	.55	.38	-.14	-.11	X_5
X_6						1.00	.80	.71	.06	.12	X_6
X_7							1.00	.75	.28	.29	X_7
X_8								1.00	.38	.37	X_8
X_9									1.00	.84	X_9
X_{10}										1.00	X_{10}

The X_2 and X_{10} are not considered to be related. The combination of these two variables very appreciably improved the correlation. Since X_5 does not distinctively influence either X_2 or X_{10}, it seems appropriate to further include X_5 in the regression analysis. By so doing, one obtained an even better correlation. If one uses either X_3 or X_4 in place of X_5 in the three-independent-vairables regression analysis, a somewhat better correlation was achieved. It should be noted however, in the above correlation matrix the X_2 is significantly dependent upon X_3 and X_4. The ultimate enhancement in the correlation was achieved by combining X_2, X_3, X_4, X_{10} or X_2, X_3, X_5, X_{10}. The above arguments are based on the following statistics:

Independent variables	R	F	P
(1) X_2	0.510	14.10	8.42E-4
(2) X_{10}	0.395	7.41	9.33E-3
(3) X_2, X_{10}	0.740	23.63	6.80E-6
(4) X_2, X_5, X_{10}	0.774	18.96	4.84E-6
(5) X_2, X_4, X_{10}	0.787	20.66	3.12E-6
(6) X_2, X_3, X_{10}	0.790	21.08	2.82E-6
(7) X_2, X_3, X_4, X_{10}	0.824	19.53	1.63E-6
(8) X_2, X_3, X_5, X_{10}	0.831	20.66	1.23E-6

Surprisingly, the addition of X_8 (soluble eq.Na_2O in kg/m^3 of mortar) as the fifth independent variable did not provide any improvement in the correlation exercise. The best correlation equation is :

$$X_1 = B_1 + B_2X_2 + B_3X_3 + B_5X_5 + B_{10}X_{10}, \text{ where}$$

B_1 = 46.7159

B_2 = - 0.3787 Beta 2 = - 0.800

B_3 = - 0.1656 Beta 3 = - 0.333

B_5 = - 0.2658 Beta 5 = - 0.262

B_{10} = 1.2388 Beta 10= 0.493 .

The significance of the above results is that, X_2, the cement replacement by an SCM is the major factor in reducing the rate of mortar expansion. However, this parameter is significantly dependent on X_3 and X_4. For the cement and the aggregate used, one may estimate the optimum cement replacement level by specifying a target rate of expansion and filling in the values of eq.Na_2O, (SiO_2 + Al_2O_3 + Fe_2O_3), and -45 micron content, all in % by mass of the SCM.

2. Concretes of Pittsburgh aggregate (data in Table XIX)

The rates of expansion are available for 46 of the 52 concretes. Therefore, the regression analysis was based on 46 sets of observations. The single-correlation matrix of the ten variables is as follows:

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	
X_1	1.00	-.12	-.00	-.06	.00	.48	.35	.78	.81	.83	X_1
X_2		1.00	-.64	-.44	-.03	-.16	.11	-.25	.15	-.07	X_2
X_3			1.00	.35	-.15	-.04	-.16	.14	.04	.04	X_3
X_4				1.00	.46	.38	.09	.15	-.25	-.27	X_4
X_5					1.00	.50	.51	.28	-.13	-.12	X_5
X_6						1.00	.69	.70	.18	.23	X_6
X_7							1.00	.52	.18	.11	X_7
X_8								1.00	.54	.52	X_8
X_9									1.00	.87	X_9
X_{10}										1.00	X_{10}

Evidently, the meaningful single-correlations are between X_1 and X_8, or X_9, or X_{10}. The positive correlation between X_1 and X_6 or X_7 is judged to be meaningless and should be rejected. Individually, the X_2, X_3, X_4, and X_5 play no significant role in the regression. But the X_2 and X_3 interact with X_1 appreciably in the multiple-regression analysis, although not as stronly as in the cases of the mortars:

Independent variables	R	F	P
(1) X_8	0.783	69.77	5.17E-7
(2) X_9	0.807	81.91	2.55E-7
(3) X_{10}	0.828	95.89	1.30E-7
(4) X_2, X_9	0.842	52.46	1.23E-7
(5) X_8, X_{10}	0.925	126.94	3.90E-9
(6) X_9, X_{10}	0.847	54.68	1.03E-7
(7) X_2, X_3, X_9	0.881	48.51	4.39E-8
(8) $X_2, X_3, X_4, X_5, X_6, X_8$	0.831	14.51	1.68E-6
(9) $X_2, X_3, X_4, X_5, X_6, X_7, X_8$	0.831	12.12	3.01E-6

Apparently, the above 9 combinations of the variables all yielded highly significant correlations. But judging by

the values of beta coefficient in each combination, some variables are actually very minor contributors to the rate of expansion.

The variables combinations (1) and (2) are really meaningful, because a rate of expansion is directly proportional to either soluble or total alkali content in concrete. The drawback of this kind of correlations is that the cement replacement level, X_2, is not explicitly expressed in the equation. However, one may still estimate it for a particular expansion rate if soluble and total alkalis are determined for the cement and the fly ash. The correlations (5) and (6) are also useful but have the same drawback.

The most useful significant correlation is (7), which incorporates cement replacement level X_2, the sum of acidic oxides X_3, and total alkali of concrete X_9. The partial coefficients of correlation and the corresponding Beta coefficients of the above useful correlations are listed below:

(1) $X_1 = B_1 + B_8X_8$

$B_1 = -2.4328$
$B_8 = 5.2513$ Beta 8 = 0.783

(2) $X_1 = B_1 + B_9X_9$

$B_1 = -0.3561$
$B_9 = 1.5068$ Beta 9 = 0.807

(5) $X_1 = B_1 + B_8X_8 + B_{10}X_{10}$

$B_1 = -2.0732$
$B_8 = 3.2369$ Beta 8 = 0.483
$B_{10} = 1.1178$ Beta 10= 0.576

(6) $X_1 = B_1 + B_9X_9 + B_{10}X_{10}$

$B_1 = 0.6816$
$B_9 = 0.6701$ Beta 9 = 0.359
$B_{10} = 1.0037$ Beta 10= 0.517

(7) $X_1 = B_1 + B_2X_2 + B_3X_3 + B_9X_9$

$B_1 = 10.7412$
$B_2 = -0.1436$ Beta 2 =-0.472
$B_3 = -0.1056$ Beta 3 =-0.342
$B_9 = 1.6697$ Beta 9 = 0.894

CONCLUSIONS

1. Among the three aggregates which were finally chosen for expansion study in combination with the high alkali cement B, only the Lady Evelyn Lake and the Pittsburgh aggregates were reactive. The former was alkali-silica reactive and expanded only in the ASTM C227 mortar bars. The latter was alkali-carbonate reactive and showed expansions in CSA A23.2-14A concrete prisms. The Trois Rivieres aggregate has not been expanding in mortar or concrete up to two years, probably due to insufficient reactive mineral content.

2. The multiple-linear-regression analyses revealed that for the mortars of the Lady Evelyn Lake aggregate, a rate of expansion could be estimated from the percentage of cement replaced by an SCM and three characteristics of the SCM used, namely, total alkali content, the sum $SiO_2+Al_2O_3+Fe_2O_3$, and minus 45 micron fine content. Apparently, the required cement replacement level would be affected by the characteristics of SCM.

   In the cases of concretes containing the Pittsburgh aggregate, a rate of expansion is related to total alkali content of concrete, cement replacement level, and the sum $SiO_2+Al_2O_3+Fe_2O_3$ of SCM.

3. The SCM's which were effective in reducing alkali-silica expansion and their optimum cement replacements levels required to achieve performance equivalent to low alkali cement performance are listed below, along with their pessimum levels:

	Optimum %	Pessimum %
Fly ash L1	40	10
Fly ash D	40	10
Fly ash L2	30-40	10
Fly ash S	30-40	10
Slag S	>65	35
Slag A1	>65	35
Slag A2	60	20
Condensed silica fume S	15	5
Condensed silica fume C	>15	5
Natural pozzolan Q	>30	10
Natural pozzolan A	<30	10

4. The SCM's which were useful in combating alkali-carbonate expansion of concrete are as follows:

	Optimum %
Fly ash L1	50
Fly ash D	40-50
Fly ash L2	50
Fly ash S	50
Slag S	50-65
Slag A1	50-65
Slag A2	>60
Condensed silica fume S	>>15
Natural pozzolan Q	>>30
Natural pozzolan A	20-30

It was noticed that the condensed silica fume and the natural pozzolans were less effective in reducing alkali-carbonate expansion than alkali-silica expansion. The reverse was true for the slags.

5. According to the ASTM C441 test only the natural pozzolan A and the two condensed silica fumes meet the criteria for being acceptably effective SCM's in preventing AAR. The fly ashes T, the slag S, and the natural pozzolan Q were close to being acceptable. This finding is very different from the conclusions of the mortar bar and concrete prism tests. Because Pyrex aggregate is very reactive and contains a significant quantity of alkalis that are slowly released into solution, and the fixed 25% cement replacement by volume is not necessarily at optimum, the use of this test to evaluate SCM's may be overly pessimistic [60,108-109].

6. At a constant W/(C+SCM) ratio, most of the fly ashes have increased concrete slumps.

7. The fly ashes L1, L2, D, and S which were effective inhibitors of AAR had adverse effects on concrete strengths, particularly at the 50% cement replacement level. This problem may be overcome by the addition of condensed silica fume to the concrete. This needs to be confirmed by further testing. The fly ashes F, T, E, and H which performed poorly in reducing AAR had beneficial effects on concrete strenth development. The effects of these fly ashes on AAR should be tested at even higher cement replacement levels, such as 60-65%.

8. The effects of high cement replacements by the SCM's on concrete setting time and early strengths have not been investigated in this study. However, changes in these concrete properties should be taken into consideration when using an SCM for the purpose of reducing concrete alkali-aggregate expansion.

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REFERENCES

1. Dolar-Mantuani, L.M.M. "Handbook of Concrete Aggregates; A Petrographic and Technical Evaluation", first ed.; Noyes Publication; 1983; Chapter 7, Alkali-Aggregate Reactivity, p.79-125.

2. Rogers, C.A. and Worton, S. "Alkali-Aggregate Reactions in Canada, A Bibliography"; Report EM-73, 2nd revised ed.; Ontario Ministry of Transportation and Communications; May, 1985.

3. Rogers, C.A. and Worton, S. "Alkali-Carbonate Reactions - A Bibliography"; Report EM-74; Ontario Ministry of Transportation and Communications; September, 1985.

4. Figg, J.W. "Alkali-Aggregate Reactivity. A Bibliography"; CEMBUREAU, Paris; September, 1977.

5. 7th Int. Conf. on Alkali-Aggregate Reaction; Carleton Univ., Ottawa, Canada; Aug.18-20, 1986.

6. Proc. 6th Int. Conf. on Alkalis in Concrete, Research and Practice; Copenhagen, Denmark; June 1983; Editors: Idorn, G.M. and Rostam, S.; Publisher: Dansk Betonforening.

7. Proc. 5th Int. Conf. on Alkali-Aggregate Reaction in Concrete; Cape Town, South Africa; March-April 1981; Editor: Oberholster, R.E., Publisher: National Building Research Institute, CSIR, South Africa.

8. Prp. 4th Int. Conf. on Effects of Alkalies in Cement and Concrete; Purdue Univ., West Lafayette, Indiana, U.S.A.; June 1978; Editor: Diamond, S.; Publisher: School of Engineering, Purdue Univ.

9. Proc. 3rd Int. Conf. on the Effect of Alkalies on the Properties of Concrete; London, U.K.; September 1976; Editor: Poole, A.B.; Publisher: Cement and Concrete Association, Waxham Springs, Slough, U.K..

10. Symposium 16 on Alkali-Aggregate Reaction, Preventive Measures; Reykjarik, Iceland; August 1975, 270p.

11. Regourd, M. and Volant, J. "Durability of Cements, Pastes, Mortars, and Concretes"; Cement Research Progress; Cement Division of American Ceramic Society; 1985.

12. Calleja, J. "Durability"; Proc. 7th Int. Congr. Chem. of Cem.; Paris, France; Vol.I, VII-2/11- 2/20; 1980.

13. Rogers, C.A. "Evaluation of the Potential for Expansion and Cracking of Concrete Caused by the Alkali-Carbonate Reaction"; Cement, Concrete, and Aggregate; 8(1): 12-23; September 1986.

14. Grattan-Bellew, P.E. "Re-evaluation of Standard Mortar Bar and Concrete Prism Tests for Alkali-Aggregate Reactivity"; Mater. Constr.; 16(94): 243-250; 1983.

15. Nixon, P.J. and Bollinghause, R. "The Effect of Alkali-Aggregate Reaction on the Tensile and Compressive Strength of Concrete"; Durab. Build. Mater.; 2(3): 243-248; 1985.

16. Swamy, R.N. and Al-Asali, M.M. "Influence of Alkali-Silica Reaction on the Engineering Properties of Concrete"; Alkali in Concrete; Editor: Dodson, V.H.; ASTM STP 930; American Society for Testing and Materials, Philadelphia; 1986.

17. Barker, A.F. "The Influence of Alkali-Silica Reactivity on the Development of Tensile Bond Strength"; Ref.8; 99-108.

18. Stark, D. and Bhatty, M.S.Y. "Alkali-Silica Reactivity: Effect of Alkali in Aggregate on Expansion"; Alkali in Concrete; Editor: Dodson, V.H.; ASTM STP 930; American Society for Testing and Materials, Philadelphia; 1986.

19. Van Aardt, J.H.P. and Visser, S. "Calcium Hydroxide Attack on Feldspars and Clays: Possible Relevance to Cement-Aggregate Reactions"; Cem. Concr. Res.; 1(6): 643-648; 1977.

20. Hobbs, D.W. "Expansion of Concrete due to Alkali-Silica Reaction: an Explanation"; Mag. Concr. Res.; 30(105): 215-221; 1978.

21. Hobbs, D.W. "Influence of Mix Proportions and Cement Alkali Content upon Expansion due to Alkali-Silica Reaction"; Technical Report No.534; Cement and Concrete Association; June 1980.

22. Ozol, M.A. "The Pessimum Proportion as a Reference Point in Modulating Alkali-Silica Reaction"; in Ref.10; 129-130; 1975.

23. French, W.J. "Reaction between aggregates and cement paste - an Interpretation of the Pessimum"; Q. J. Eng. Geol.; 13: 231-247; 1980.

24. Grattan-Bellew, P.E. "A Review of Test Methods for Alkali Expansivity of Concrete Aggregates"; in Ref.7; Paper S252/9.

25. Grattan-Bellew, P.E. "Canadian Experience of Alkali-Expansivity in Concrete"; in Ref.7; Paper S252/6.

26. CSA Standard CAN3-A23.1-M77, Concrete Materials and Methods of Concrete Construction. Appendix B4.

27. Grattan-Bellew, P.E., Dolar-Mantuani, L.M.M., and Sereda, J.J. "The Aggregate Shortage and High Alkali Cement in Changing Energy Situation"; Can. J. Civil Eng.; 5(2): 250-261; 1978.

28. "Perspectives on Canadian Research on Alkali-Aggregate Reactivity"; Session I of the Conference in Ref.5.

29. Stark, D. "Alkali-Silica Reactivity: Some Reconsiderations"; Cem. Concr. Aggr.; 2(2): 92-94; 1980.

30. Proc. Intern. Symp. on the Use of PFA in Concr.; Univ. of Leeds, U.K.; April 14-16, 1982; Editors: Cabrera, J.A. and Cusens, A.R..

31. Pro. First Int. Conf. on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-products in Concrete; Montebello, Canada; July 31-August 5, 1983; Editor: Malhotra, V.M.; ACI Publication SP-79; American Concrete Institute, Detroit.

32. Proc. 2nd Int. Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete; Madrid, Spain; April 21-25, 1986; Editor: Malhotra, V.M., ACI Publication SP-91; American Concrete Institute, Detroit.

33. Berry, E.E. and Malhotra, V.M. "Fly Ash in Concrete", CANMET SP85-3, Ministry of Supply and Services Canada; 1986.

34. Proc. Symp. Fly Ash and Coal Conversion By-products: Characterization, Utilization, and Disposal; Boston, Ma., U.S.A.; November 1984; Editors: McCarthy, G.J. and Lauf, R.J.; Materials Research Society, Vol.43, 1985.

35. Proc. Symp. on Effect of Fly Ash Incorporation in Cement and Concrete; Boston, Ma., U.S.A.; November 16-18, 1981; Editor: Diamond, S.; Material Research Society.

36. Proc. 6th Int. Symp. on Fly Ash Utilization; Reno, Nevada, U.S.A.; March 1982; National Ash Association, Washington, D.C.; July 1982.

37. Proc. 4th Int. Ash Utilization Symp.; St. Louis, Mo.; Mar.24-25, 1976, .

38. Proc. 2nd Int. Ash Utilization Symp.; Pittsburgh, Pa.; Mar. 10-11, 1970.

39. Proc. Sym. on Use of Pozzolanic Materials in Mortars and Concretes; San Francisco, Ca., U.S.A.; October 12, 1949; ASTM STP #99; American Society for Testing and Materials, Philadelphia, U. S. A..

40. Jarrige, A. "Les Cendres Volantes"; Eyrolles, Paris, France; 1971.

41. Mielenz, R.C. "Mineral Admixtures - History and Background"; Concr. Intern.; 34-42; August 1983.

42. Kovacs, R. "Utilization of Fly Ash in Cement Industry"; TIZ-Fachberichte; 106(9): 658-663; 1982; English translation by Amerongen, C.V., Blue Circle Industries.

43. Malhotra, V.M. and Carette, G.G. "Silica Fume"; Concr. Constr.; 27(5): 443-446; May 1982.

44. Hogan, F.J. "The Effect of Blast Furnace Slag Cement on Alkali Aggregate Reactivity: A Literature Review"; Cem. Concr, Aggr.; 7(2): 100-107; 1985.

45. Hobbs, D.W. "Deleterious Expansion of Concrete due to Alkali-Silica Reaction: Influence of PFA and Slag"; Mag. Concr. Res.; 38(137): 191-205; 1986.

46. Sprung, S. and Adabian, M. "The Effect of Admixtures on Alkali-Aggregate Reaction in Concrete"; in Ref.9; 125-137; 1976.

47. Asgeirsson, H. and Gudmundson, G. "Pozzolanic Activity of Silica Dust"; Cem. Conc. Res.; 9(2): 249-252; 1979.

48. Oberholster, R.E. and Westra, W.B. "The Effectiveness of mineral admixtures in reducing expansion due to alkali-Aggregate Reaction with Malmesbury Group Aggregates"; in Ref. 7; S252/31; 1981.

49. Aitcin, P.C.(Ed.) "Condensed Silica Fume"; University of Sherbrooke, Quebec, Canada; 1983; 52pp.

50. Hjorth, L. "Microsilica in Concrete"; a Review Published by Aalborg Portland, Denmark; 1982.

51. Sellevold, E.J. and Nielsen, T. "Condensed Silica Fume in Concrete: A World Review"; CEMBUREAU, Paris, France; 1986; also in Ref.52; Paper #1; 1987.

52. Intern. Workshop on Condensed Silica Fume in Concrete, Compilation of Papers; Montreal, Canada; 1987.

53. Popovic, K., Ukraincik, V. and Djurekovic, A. "Improvement of Mortar and Concrete Durability by the Use of Condensed Silica Fume"; Durab. Build. Mater.; 2(1): 171-186; 1984.

54. Aitcin, P.C. and Regourd, M. "The Use of Condensed Silica Fume to Control Alkali-Silica Reaction - A Field Case Study"; Cement Concr. Res.; 15(4): 711-719; 1985.

55. Perry, C. and Gillott, J.E. "The Feasibility of Using Silica Fume to Control Concrete Expansion due to Alkali Aggregate Reactions"; Durab. Build. Mater.; 3: 133-146; 1985.

56. Gillott, J.E. "The Influence of Silica Fume on Alkali-Aggregate Reaction"; in Ref. 52; Paper #12; 1987.

57. Oberholster, R.E. and Davies, G. "The Effect of Mineral Admixtures on the Alkali-Silica Expansion of Concrete under Outdoor Exposure Conditions"; in Ref.5; 1986.

58. Johnston, C.D. "Influence of Alkali Equivalent and Amount of Cement and Fly Ash on Alkali-Silica Expansion of Concrete Mixtures"; in Ref.5; 1986.

59. Perry, C., Day, R., Joshi, R.C., Langan, B.W., and Gillott, J.E. "The Effectiveness of Twelve Canadian Fly Ashes in Suppressing Expansion due to Alkali-Silica Reaction", in Ref.5; 1986.

60. Hobbs, D.W. "Influence of Pulverized-Fuel Ash and Granulated Blastfurnace Slag upon Expansion Caused by the Alkali-Silica Reaction"; Mag. Concr. Res.; 34(119): 83-94; 1982.

61. Davis, R.E. "Pozzolanic Materials - with Special Reference to Their Use in Concrete"; Tech. Memo.; 1954; American Concrete Pipe Association.

62. Roy, D.M. and Idorn, G.M. "Hydration, Structure, and Properties of Blast Furnace Slag Cements, Mortars, and Concrete"; J. Am. Concr. Inst.; 444-457; Nov/Dec 1982.

63. Bakker, R.F.M. "About the Cause of the Resistance of Blast Furnace Cement Concrete to the Alkali-Silica Reaction"; in Ref.7; 1981.

64. Smolczyk, H.G. "Investigation on the Diffusion of Na-ion in Concrete"; in Ref.10; 183-188; 1976.

65. Smolczyk, H.G. "Slag Structure and Identification of Slags"; Proc. 7th Intern. Congr. Chem. Cem.; Paris, France; Vol.I: III-1/3-III-1/11; 1980.

66. Gjorv, O.E. and Vennesland, O. "Diffusion of Chloride Ion from Sea Water"; Cem. Concr. Res.; 9(2): 229-238; 1979.

67. Parker, K.M. and Roy, D.M. "Porosity, Permeability, and Microstructure of Portland-Blast Furnace Slag Cement Pastes"; Am. Ceram. Soc. Bull.; 61: 345; 1982.

68. Delage, P. and Aitcin, P-C. "Influence of Condensed Silica Fume on the Pore-Size Distribution of Concrete"; Ind. Eng. Chem. Prod. Res. Dev.; 22: 286-290; 1983.

69. Mehta, P.K. and Gjorv, O.E. "Properties of Portland Cement Containing Fly Ash and Condensed Silica Fume"; Cem. Concr. Res.; 12(5): 587-595; 1982.

70. Bakker, R.F.M. "La Durabilities de Betons de Cement de Haut Fourneau"; Silicates Industriels; VLXII(3): 91-95; 1982.

71. Manmohan, D. and Mehta, P.K. "Influence on Pozzolanic, Slag, and Chemical Admixtures on Pore Size Distribution and Permeability of Hardened Cement Paste"; Cem. Concr. Aggr.; 3(1): 63-67; Summer 1981.

72. Feldman, R. "Pore Size Formation during Hydration of Fly Ash and Slag Cement Blend"; in Ref.35: 124-133; 1981.

73. Sellevold, E.J., Bager, D.H., Jensen, E.K., and Knudsen, T. "Silica Fume Cement Pastes - Hydration and Pore Structure"; Proc. Nordisk Mini Seminar on Silica in Concrete"; Dec. 1981.

74. Gjorv, O.E. "Durability of Concrete Containing Condensed Silica Fume"; in Ref.31; 2:695-708; 1983.

75. Roy, D.M. and Parker, K.M. "Microstructure and Properties of Granulated Slag-Portland Cement Blends at Normal and Elevated Temperatures"; in Ref.31; 1: 397-414; 1983.

76. Bakker, R.F.M. "Permeability of Blended Cement Concretes"; in Ref.31; 1: 589-606; 1983.

77. Marsh, B.K., Day, R.L. and Bonner, D.G. "Pore Structure Characteristics Affecting the Permeability of Cement Paste Containing Fly Ash"; Cem. Concr. Res.; 15(6): 1027-1038; 1985.

78. Feldman, R.F. "Significance of Porosity Measurements on Blended Cement Performance"; in Ref.31; 1: 415-434; 1983.

79. Hooton, R.D. "Permeability and Pore Structure of Cement Pastes Containing Fly Ash, Slag, and Silica Fume"; Blended Cements; Editor: Fronshdorff, G.; ASTM STP 897; American Society for Testing and Materials, Philadelphia; 128-134; 1984.

80. Feldman, R.F. "Microstructure Investigation of Cements and Mortars Containing Condensed Silica Fume"; in Ref.52; Paper #6; 1987.

81. Feldman, R.F. "The Effect of Sand/Cement Ratio and Silica Fume on the Microstructure of Mortars"; Cem. Concr. Res.; 16(1): 31-39; 1986.

82. Hooton, R.D. "Some Aspects of Durability with Condensed Fume in Pastes, Mortars and Concretes"; in Ref.52; Paper #19; 1987.

83. Regourd, M., Thomassin, J.H., Baillif, P., and Touray, J.C. "Blast Furnace Slag Hydration. Surface Analysis"; Cem. Concr. Res.; 13(4): 549-556; 1983.

84. Bhatty, M.S.Y. and Greening, N.R. "Interaction of Alkalies with Hydrating and Hydrated Calcium Silicates"; in Ref.8; 87-111; 1978.

85. Bhatty, M.S.Y. "Mechanism of Pozzolanic Reactions and Control of Alkali-Aggregate Expansion"; Cem. Concr. Aggr.; 7(2): 69-77; Winter 1985.

86. Rayment, P.L. "The Effect of Pulverized-Fuel Ash on the C/S Molar Ratio and Alkali Content of Calcium Silicate Hydrates in Cement"; Cem. Concr. Res.; 12(2): 133-140; 1982.

87. Tang, M.S., Ye, Y.F., Yuan, M.Q. and Zhen, S.H. "The Preventive Effect of Mineral Admixturtes on Alkali-Silica Reaction and Its Mechanism"; Cem. Concr. Res.; 13(2): 171-176 (1983).

88. Glasser, F.P. and Marr, J. "The Alkali Binding Potential of OPC and Blended Cements"; Il Cemento; 2: 85-94; 1985.

89. Diamond, S. "Effect of Microsilica on Pore Solution Chemistry of Cement Pastes"; J. Am. Ceram. Soc.; 66: 5; 1983.

90. Diamond, S. "A Review of Alkali-Silica Reaction and Expansion Mechanisms: Part I, Alkali in Cement and Concrete Pore Solutions"; Cem. Concr. Res.; 5(4): 329-346; 1975.

91. Page, C.L. and Vennesland, O. "Pore Solution Composition and Chloride Binding Capacity of Silica Fume Cement Pastes"; Mater. Struct., RILEM; 16(91): 19-25; 1983.

92. Diamond, S. "Effects of Two Danish Flyashes on Alkali Contents of Pore Solution of Cements-Flyash Pastes"; Cem. Concr. Res.; 11(3): 383- 394; 1981.

93. Kawamura, M., Takemoto, K., and Hasaba, S. "Effect of Silica Fume on Alkali-Silica Expansion in Mortars"; in Ref.32; 2: 999-1012; 1986.

94. Verbec, G.J. and Gramlich, C. "Osmotic Studies and Hypothesis Concerning Alkali-Aggregate Reaction"; Proc. Am. Soc. Test. Mater.; 55: 1110-1128; 1955; also Research Dept. Bulletin 57; Portland Cement Association; Chicago; 1956.

95. Power, T.C. and Steinour, H.H. "An Interpretation of Published Researches on the Alkali-Aggregate Reaction"; J. Am. Concr. Inst.; Feb/April 1955; Proc.; 51: 497-516, 785-812; also Research Dept. Bulletin 55; Portland Cement Association; Chicago; 1955.

96. Regourd, M. "Microstructure of Cement Based Materials Containing Silica Fume. Its Relationship with Some Properties"; in Ref.52; Paper #7; 1987.

97. Marcdargent, S. "Methode d'Echange Eau-Methanol pour l'Etude des Milieux Poreux Humides"; Lafarge Coppee Recherche; 1982.

98. Parrott, L.J. "Thermogravimetric and Sorption Studies of Methanol Exchange in an Alite Paste"; Cem. Concr. Res.; 13(1): 18-22; 1983.

99. Diamond, S. "On the Glass Present in Low-Calcium and in High-Calcium Fly AAshes"; Cem. Concr. Res.; 13(4): 459-464; 1983.

100. Dolar-Mantuani, L.M.M. "Alkali-Silica Reactive Rocks in the Canadian Shield"; Highway Res. Rec. Bull.; No.268: 99-117; 1969.

101. St. John, D.A. "The Application of Microscopy in the Determination of Alkali-Aggregate Reaction"; in Proc. 7th Intern. Conf. on Cement Microscopy; Mar 1985; Ft. Worth, Tx; p.395-406.

102. Hadley, D.W. "Alkali Reactivity of Dolomitic Carbonate Rocks - Expansion and Dedolomitization"; oc. Highway Research Board; 40: 462-474; 1961.

103. Hadley, D.W. "Alkali Reactivity of Dolomitic carbonate Rocks"; Highway Research Record 45; Symp. on Alkali-Carbonate Rock Reactions; 1-20.

104. Helmuth, R.A. "Water-Reducing Properties of Fly Ash in Cement Pastes, Mortars, and Concretes: Causes and Test Methods"; in Ref.29; 1:723-740; 1986.

105. Rossouw, E. and Kruger, J. "Review of Specifications for Additions for Use in Concretes"; in Ref.31; 1: 201-220; 1983.

106. Berard, J. "Alkali-Silica Case History in Quebec";CSA A5 Seminar on Cement-Aggregate Reactivity; May 1982; Montreal, Quebec.

107. Levin, R.I. Statistics for Management; 2nd Ed.; Prentice-Hall, Inc.; Englewood Cliffs, N.J.; 1981; p.419.

108. Dunstan, E.R.Jr. "Thee Effect of Fly Ash on Concrete Alkali-Aggregate Reaction"; Cem. Concr. Aggr.; 3(2): 101-104; 1981.

109. Elmhirst, N.R. "The Effectiveness of Blast Furnace Slag and Fly Ash on Controlling Alkali-Silica and Alkali-Carbonate Reactions"; Canada Cement Lafarge Ltd.; Sept. 1983.

Table I

Cement Characteristics

	High Alkali Cement B	Low Alkali Cement K	High Alkali Cement M
SiO_2	20.96	22.17	20.69
Al_2O_3	4.32	4.06	4.52
TiO_2	0.18	0.14	0.25
P_2O_5	0.10	0.10	0.16
Fe_2O_3	2.41	2.67	2.92
T-CaO	63.17	63.42	61.11
SrO	0.13	0.06	0.11
MgO	2.49	1.94	3.65
Na_2O	0.33	0.16	0.42
K_2O	1.04	0.40	1.10
SO_3	2.93	2.84	3.01
Loss	2.05	1.32	2.08
Total	100.11	99.28	100.02
Free CaO	0.84	0.98	0.39
Soluble Na_2O	0.08	nil	0.19
Soluble K_2O	0.80	0.19	0.92
Total Alkalies (as Na_2O equiv)	1.01	0.42	1.14
Soluble Alkalies (as Na_2O equiv)	0.61	0.12	0.79
Bogue Potential Compounds*			
C_4AF	7.3	8.1	8.9
C_3A	8.1	6.9	8.1
C_3S	55.4	46.4	48.3
C_2S	18.3	28.5	22.9
$CaSO_4$	3.5	4.9	3.3
Na_2SO_4	0.8	0.4	1.0
K_2SO_4	1.9	0.7	2.0

* In calculation, the Al_2O_3 value includes P_2O_5 and TiO_2, and the CaO excludes free CaO. the SO_3 is assumed to combine with Na_2O and K_2O first, and then with CaO.

Table II

Fly Ash Characteristics Data

Fly Ash	L1 N.B.	D N.B.	S Alta.	F Alta.	L2 Ont.	T Ont.	E Sask.	H U.S.A.
SiO_2	44.93	36.76	54.69	56.70	41.73	41.81	44.86	40.33
Al_2O_3	25.79	14.81	25.02	21.66	25.48	22.69	23.76	22.92
Fe_2O_3	19.06	36.16	4.13	5.05	13.77	3.89	3.62	4.59
FeO	0.92	1.84						
CaO	1.43	5.84	12.49	8.54	3.96	12.86	12.98	22.98
MgO	.82	.10	1.25	1.22	.64	3.09	3.11	4.83
Na_2O	0.48	0.16	1.67	4.83	0.53	5.74	7.00	1.84
K_2O	3.00	1.43	.50	.88	1.41	.80	0.69	0.38
SO_3	.67	1.34	.30	.34	1.40	7.81	.80	1.56
Loss*	2.88	.88	.29	.29	8.72	1.33	.65	0.56
Total	99.98	99.32	100.34	99.51	100.12	99.22	97.47	99.99
Other element present			Ba		Ba	Ba	Ba(1.80)	
Total alkali eq. Na_2O	2.45	1.10	2.00	5.41	1.46	6.27	7.45	2.07
Soluble alkali	.07	.03	.00	0.06	.04	2.26	.30	0.16
Carbon	1.40	0.58	0.39	.05	7.55	0.17	0.72	0.71
Density g/cm^3	2.58	3.01	2.14	1.82	2.48	2.55	2.45	2.54
Blaine cm^2/g	3190	2220	3600	3390	4880	6120	3250	3700
% passing 325 mesh	85.5	83.2	81.0	88.9	81.1	96.7	80.0	83.9
Pozzolanic activity ≠ with cement - % @ 28-d	94	90	89	83	91	141	95	90
with lime, MPa @ 7-d	6.7	8.9	6.9	5.7	7.8	15.1	6.4	5.8

* Fly ash @ 750°C
≠ ASTM C311

Table III

Condensed Silica Fume, Natural Pozzolan and Slag characteristics

	Condensed Silica F.		Natural Pozzolan		Slag		
	S Quebec	C Quebec	Q B.C.	A N.S.	S Ont.	A1 N.Y.	A2 Ont.
SiO_2	95.41	74.73	62.37	88.31	38.86	35.83	36.49
Al_2O_3	.09	.60	16.22	.66	6.57	9.16	8.21
Fe_2O_3		2.08	5.35		1.06	.81	0.86
CaO	.32	1.03	4.34	.07	34.22	39.72	33.42
MgO	.73	1.09	2.16		12.36	9.51	15.55
Na_2O	.02	.10	3.44	.02	.30	.12	0.30
K_2O	.74	3.80	3.16	.06	.52	.28	0.55
SO_3	.24	2.37	.08	.14	3.25	2.99	2.80
Mn_2O_3		6.40			1.50	.70	1.50
Loss*	1.80	6.51	2.23	11.25	-0.38	-1.03	-1.02
Total	99.35	98.71	99.35	100.51	98.26	98.09	99.68
Other element present		Zn	Ba		Ba	Ba	
Total alkali	.51	2.60	5.52	.06	.64	.30	0.66
Soluble alkali	.12	1.77	.06	0.04	.01	.01	0.08
Carbon content	1.71	1.91	0.14	0.64	0.62	0.36	0.35
Specific gravity g/c.c.	2.42	2.48	2.73	2.44	3.00	3.04	2.89
Blaine cm^2/g	43,750	41,700	7670	28,890	4280	5980	5260
% passing 325 mesh	98.3	91.1	98.3	97.8	82.9	98.5	97.0
Pozzolanic activity ≠ with cement - % (@ 28d)	119	93	95	82	93°	114°	97°
with lime, MPa (@ 7-d)	12.5	14.2	9.4	4.9	6.9	10.0	7.9

* Slag @ 1050°C, other 4 samples @ 750°C
≠ ASTM C311
° Combined effect of slag hydraulic and pozzolanic properties

Table IV

The Phases Found in SCM's by XRD

SCM's	Amorphous Peak Position 2	Crystalline Phases								
		-Quartz	$-Fe_2O_3$	Fe_3O_4	Mullite A_3S_2	Melilite C_2AS	Anorthite CAS_2	Akermanite C_2MS_2	$CaSO_4$	Na_2SO_4
Fly Ashes										
- L1, N. S.	23.0	*	*	*	*	-	-	-	-	-
- D, N.B.	22.5	*	*	*	-	-	-	-	-	-
- L2, Ont.	22.7	*	*	*	*	-	-	-	-	-
- S, Alta.	23.0	*	*	-	*	-	-	-	-	-
- F, Alta	24.5	*	-	-	-	-	-	-	-	-
- T, Ont	27.5	*	-	-	*	-	-	-	-	-
- E, Sask.	27.5	*	*	-	-	-	-	-	*	*
- H, Texas	28.9	*	*	-	*	-	-	-	-	-
Slags										
- S, Ont.	30.5	*	*	-	-	-	-	*	-	-
- A1, N.Y.	31.0	-	*	-	-	-	-	-	-	-
- A2, Ont.	30.0	-	-	-	-	-	-	-	-	-
Silica Fume										
- S, Que.	21.8	*	-	*	-	-	-	-	-	-
- C, Que.	21.5	*	-	*	-	-	-	-	-	-
Natural Pozzolans										
- Q, B.C.	22.5	*	-	-	-	*	*	-	-	-
- A, N.S.	22.5	*	*	-	-	-	-	-	-	-

(*) Probable Phase
* Present
\- Absent

Table V

ASTM C-289 and PCA Osmatic Test Results of Rocks

Sample I.D.	ASTM (C-289) (1)		PCA Osmotic Cell	
	Reduction in alkalinity Rc (m-mole/l)	Dissolved Silica Sc (m-mole/l)	Flow Rate (mm/day) (1)	Flow Rate (mm/day) (2)
Nairn Falls #1 (bed rock)	32	32	0.40 (@ 42 days) 0.31 (@ 87 days)	7.50 (@ 42 days) 2.25 (@ 87 days)
Nairn Falls #2 (outcrop)	-	-	0.00 (@115 days)	-
Nairn Falls #3 (outcrop)	102	15	0.39 (@115 days)	-
Lady Evelyn Lake	47	100	0.70 (@12 days) 0.54 (@57 days)	1.60 (@12 days) 1.33 (@57 days)
Trois Rivieres	128	29	0.00 (@12 days) 0.11 (@72 days)	0.00 (@28 days) 0.22 (@72 days)
Pittsburgh Quarry #1	83	13	1.86 (@115 days)	-
Pittsburgh Quarry #2	130	13	0.36 (@115 days)	-

(1) Tested at a sample fineness of - #50 + #100 mesh
(2) Tested at a sample fineness of - #100 + #200 mesh

Table VI

ASTM C-227 Mortar Bar Expansion Data of Rocks

	H_2O%	Flow,%	2 weeks	4 weeks	2 mos.	3 mos.	4 mos	6 mos.	9 mos.
Nairn Falls #1 (bedrock)									
with Cement M	50.3	105	0.003	0.010	0.024	0.034	0.048	0.083	0.109
with Cement K	50.7	119	0.001	-0.001	0.004	0.005	0.009	0.017	0.023
Nairn Falls #2 (outcrop)									
with Cement M	50.7	107	0.003	0.006	0.014	0.018	0.024	0.024	0.031
with Cement K	49.8	117	-0.006	-0.002	0.004	0.008	0.012	0.012	0.010
Lady Evelyn Lake									
with Cement M	52.2	106	0.004	0.013	0.049	0.102	0.157	0.256	0.316
with Cement K	49.7	116	0.002	-0.005	0.001	0.002	0.002	0.010	0.012
Trois Rivieres									
with Cement M	50.7	110	0.003	0.009	0.023	0.033	0.047	0.078	0.109
with Cement K	50.3	119	-0.005	0.005	0.001	0.001	0.003	0.007	0.009
Pittsburg #1									
with Cement M	50.7	105	0.009	0.022	0.030	0.037	0.040	0.050	0.060
with Cement K	49.7	110	-0.004	0.004	0.008	0.010	0.012	0.019	0.025
Pittsburg #2 (face)									
with Cement M	51.2	117	0.021	0.036	0.048	0.057	0.062	0.075	0.086
with Cement K	49.7	115	-0.002	0.008	0.009	0.013	0.016	0.026	0.033

Table VII

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Lady Evelyn Lake W/ (C+SCM) = 0.53

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength(MPa) 28-day	84-day
Control		2438	75	1.9	33.1	37.6
Fly Ash						
L1, N.S.	10%		70	2.1	31.0	39.5
	20		90	1.4	27.9	38.8
	30		100	1.3	25.4	35.4
	40		150	1.9	24.8	33.5
	50	2431	180	1.1	16.8	23.5
D, N.B.	10%		100	2.2	27.8	34.1
	20		100	2.1	27.0	33.9
	30		120	1.8	23.8	32.2
	40		110	1.9	23.2	31.7
	50	2448	170	1.8	15.8	21.5
L2, Ont.	10%		90	1.5	29.0	35.4
	20		75	1.5	26.2	35.5
	30		85	1.5	27.4	35.5
	40		80	1.9	18.4	36.6
	50	2389	80	1.7	18.8	26.5
F, Alta.	20%					
	30					
	40					
S, Alta.	10%		90	1.8	30.8	37.3
	20		115	1.3	28.9	36.6
	30		160	1.1	28.6	38.4
	40		120	1.5	29.8	39.0
	50	2403	190	1.1	22.5	32.2
T, Ont.	10%		110	1.9	30.8	35.7
	20		160	1.7	32.0	38.4
	30		160	1.8	38.3	42.7
	40		170	1.3	35.8	39.3
	50	2431	195	1.4	32.6	40.0

Table VII (Cont'd)

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Lady Evelyn Lake — W/ (C+SCM) = 0.53

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength(MPa) 28-day	84-day
Fly Ash						
E, Sask.	10%		95	1.8	32.2	37.8
	20		115	1.6	34.0	39.5
	30		120	1.3	34.4	41.1
	40		170	1.1	31.4	36.3
	50	2431	185	1.0	31.2	41.0
H, Texas	30%		175	1.1	32.4	40.7
	40		150	1.1	34.2	41.6
	50	2448	165	1.0	33.6	41.8
Slag						
S, Ont.	35%		75	1.6	29.1	34.8
	50		70	1.6	26.5	31.5
	65	2431	70	1.4	23.7	27.6
A2, Ont.	20%					
	45					
	60					
A1, N. Y.	35%		70	2.0	35.2	39.9
	50		80	1.6	35.2	40.8
	65	2431	70	2.1	32.6	36.0
Condensed Silica Fume						
S, Que.	5%		70	2.0	37.1	42.2
	10		80	2.2	39.6	43.6
	15	2417	70	1.9	41.2	43.4
C, Ont.	5%		70	2.3	34.6	39.4
	10		95	2.9	36.8	43.3
	15	2374	110	3.6	39.9	43.4
Natural Pozzolan						
Q, B.C.	10%		75	1.9	30.6	34.9
	20		90	1.7	28.2	33.6
	30		85	1.8	28.5	33.5
A, N.S.	10%		85	2.0	36.1	40.1
	20		80	2.3	41.0	40.7
	30		110	1.9	34.3	37.2

Table VIII

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Trois Rivieres — W/(C+SCM) = 0.52

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength (MPa) 28-day	84-day
Control		2410	85	1.8	33.0	40.2
Fly Ash						
L1, N.S.	10%		160	1.4	30.6	38.2
	20		135	1.3	29.7	40.3
	30		150	1.3	27.2	37.7
	40		155	1.3	27.8	34.4
	50	2403	160	1.7	17.0	27.6
D, N.B.	10%		115	1.9	32.4	37.1
	20		120	1.9	28.1	32.9
	30		130	1.3	24.2	32.1
	40		170	1.3	25.1	32.0
	50	2403	195	1.5	13.1	21.1
L2, Ont.	10%		90	1.4	33.5	40.8
	20		95	1.8	32.2	40.0
	30		120	1.5	29.8	39.2
	40		120	1.5	32.4	41.6
	50	2367	80	1.7	22.0	29.0
F, Alta.	20%		100	1.4	31.4	41.5
	30		145	1.3	30.8	41.7
	40		210	1.1	29.1	40.6
S, Alta.	10%		100	1.7	33.2	40.7
	20		115	1.4	32.9	43.0
	30		170	1.3	31.2	42.1
	40		140	1.3	31.0	41.3
	50	2374	175	1.3	25.4	38.2
T, Ont.	10%		130	1.9	34.2	39.0
	20		140	1.9	38.1	43.6
	30		155	2.0	40.6	47.8
	40		175	1.4	38.4	44.1
	50					
E, Sask.	10%		110	1.6	35.8	40.5
	20		160	1.4	33.6	39.1
	30		190	1.2	33.7	44.3
	40		200	1.1	29.9	39.8
	50	2403	190	1.1	34.6	40.8

Table VIII (cont'd)

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Trois Rivieres (W/(C+SCM) = 0.52

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength(MPa) 28-day	84-day
Fly Ash						
H, Texas	30%		170	1.3	37.4	47.2
	40		190	1.2	36.6	41.1
	50	2403	200	1.1	35.2	47.7
Slag						
S, Ont.	35%		85	1.6	32.9	39.0
	50		90	1.5	29.1	38.1
	65	2403	95	1.4	23.9	32.0
A2, Ont.	20%		95	1.6	34.8	40.7
	45		105	1.7	36.6	39.6
	60	2403	150	1.3	30.2	35.1
A1, N.Y.	35%		120	1.7	37.2	33.4
	50		75	1.8	38.4	44.3
	65	2403	70	1.6	32.0	29.9
Condensed Silica Fume						
S, Que.	5%		115	2.2	42.4	47.9
	10		70	2.1	48.8	54.4
	15	2403	75	2.0	52.5	54.9
C, Que.	5%		85	2.3	38.1	42.8
	10		70	2.6	43.1	46.3
	15	2360	70	3.1	43.3	47.8
Natural Pozzolan						
Q, B.C.	10		85	3.4	34.3	38.9
	20		95	2.3	30.9	38.1
	30	2389	75	2.0	29.2	36.5
A, N.S.	10%		70	2.1	46.4	48.0
	20		80	1.8	43.1	45.8
	30	2332	70	2.0	37.8	39.8

Table IX

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Pittsburgh (W/(C+SCM) = 0.58

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength(MPa) 28-day	84-day
Control		2374	80	1.8	30.8	33.9
Fly Ash						
L1, N.S.	10%		130	1.3	27.2	31.5
	20		150	1.2	25.7	31.1
	30		150	1.2	24.2	29.9
	40		195	0.8	19.4	24.9
	50	2374	165	1.3	17.8	24.0
D, N.B.	10%		150	1.7	26.8	30.8
	20		160	1.5	25.1	30.8
	30		160	1.3	23.6	28.5
	40		180	1.0	18.8	24.6
	50	2374	200	0.8	12.9	17.6
L2, Ont.	10%		100	1.3	31.0	35.9
	20		85	1.4	30.0	36.3
	30		95	1.4	26.2	30.5
	40		110	1.4	23.4	28.2
	50	2332	100	1.4	16.0	20.5
S, Alta.	10%		135	1.5	28.2	32.2
	20		150	1.5	27.6	31.6
	30		170	1.6	25.9	28.6
	40		185	1.0	23.0	29.4
	50	2339	165	1.3	23.1	31.2
T, Ont.	10%		90	1.8	30.8	32.6
	20		120	1.8	34.4	35.2
	30		170	1.6	32.4	31.5
	40		200	1.1	24.7	26.0
	50	2367	190	1.6	32.6	35.1
E, Sask.	10%		140	1.4	30.0	32.6
	20		160	1.2	31.2	35.4
	30		170	1.2	31.8	32.9
	40		195	1.1	28.4	30.8
	50	2360	215	0.7	25.0	29.9
Slag						
S, Ont.	35%		100	1.6	28.4	32.9
	50		95	1.5	25.8	29.9
	65	2374	90	1.6	21.5	24.9

Table IX (cont'd)

Unit Weights, Slumps and Compressive Strengths of Concretes

Coarse Aggregate: Pittsburgh — W/(C+SCM) = 0.58

		Unit wt. Kg/m^3	Slump mm	% Air	Compressive Strength(MPa) 28-day	84-day
Slag						
A2, Ont.	20%		80	1.9	30.5	32.7
	45		70	1.6	33.3	35.4
	60	2374	80	1.4	27.2	30.8
A1, N.Y.	35%		90	1.8	33.0	34.9
	50		85	1.7	29.0	32.6
	65	2360	110	1.5	22.4	25.0
Condensed Silica Fume						
S, Que.	5%		105	1.8	38.8	38.6
	10		70	1.8	44.9	43.2
	15	2346	80	1.8	41.2	42.1
C, Que.	5%		90	2.4	34.2	35.7
	10		80	2.6	38.1	38.5
	15	2360	105	2.5	40.7	41.2
Natural Pozzolan						
Q, B.C.	10%		145	1.8	27.7	30.5
	20		130	1.9	26.2	28.6
	30		110	1.8	23.3	26.8
A, N.S.	10%		75	2.0	28.7	31.3
	20		70	1.9	32.6	33.4
	30		70	1.8	32.4	35.4

Table X

Test Results of ASTM C-441 Mortar Bars

	% Replacement by wt. of cement	W/C+SCM ratio	Flow %	% Expansion @ 14-d,38°C	% Reduction in Expansion	% $Ca(OH)_2$ in mortar
Control Mix	0	0.52	112	0.201	0	4.5
Fly Ash						
L1, N.S.	21.4	0.51	110	0.060	70.1	3.1
D, N.B.	24.2	0.49	114	0.105	47.8	2.6
L1, Ont.						
F, Alta.	17.5	0.54	109	0.114	43.3	2.9
S, Alta.	18.4	0.55	114	0.100	50.2	4.1
T, Ont.	21.2	0.47	106	0.030	85.1	1.6
E, Sask.	20.6	0.53	113	0.065	67.7	3.0
Slag						
S, Ont.	24.1	0.53	107	0.045	77.6	3.3
A1, N.Y.	24.3	0.52	108	0.068	66.2	2.7
Condensed Silica Fume						
S, Que.	20.4	0.71	108	-0.009	104.5	0.0
C, Que.	20.8	0.63	107	0.002	99.0	0.0
Natural pozzolan						
Q, B.C.	22.4	0.52	109	0.041	79.6	3.2
A, N.S.	20.5	0.78	106	0.010	95.0	1.3

Note: (1) Cement used: Cement B (Total eq. Na_2O 1.01%, soluble eq. Na_2O 0.61%)
(2) Mineral admixture replacement for cement was 25% by volume of cement for all mortar mixtures. W/C+SCM ratio was varied to maintain flow at 100-115%.

Table XI

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O (Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Controls																		
(H.A. Cement)																		
B	1- 4	0.480	112	8.88	5.36	2	6	20	37	40	52	53	49	53	55			
"	35- 38	0.480	112	8.88	5.36	7	13	26	36	44	60	63	62	63	66			
"	193-194	0.480	105	8.88	5.36	8	11	19	22	48	54	46	48	44	49			
"	231-232	0.485	112	8.88	5.36	4	8	27	41	66	96	130	152	164	184			
L.A. Cement																		
K	189-190	0.485	104	3.69	1.06	6	6	11	12	18	19	18	18	18	18			
Fly Ash																		
L1																		
10%	5- 6	0.48	114	10.2	4.89	2	5	13	21	27	56	75	84	96	97			
20%	7- 8	0.48	118	11.4	4.41	0	2	5	11	12	24	29	30	36	42			
30%	9- 10	0.48	119	12.7	3.94	0	0	0	3	4	18	19	21	29	30			
40%	165-166	0.48	120	14.0	3.47	9	4	8	9	12	12	12	10	11	14			
50%	199-200	0.48	127	15.2	2.99	8	8	9	10	6	9	9	3	8				
L1*																		
0%	223-224	0.485	114	11.0	7.47	9	15	34	74	106	130	173	177	181	194			
20%	225-226	0.485	119	13.1	6.03	7	7	11	22	30	30	62	81	110	136			
30%	227-228	0.485	125	14.2	5.35	7		7	15	19	23	33	42	56	73			
40%	229-230	0.485	133	15.2	4.68	7	5	8	12	15	17	22	30	40	52			
D																		
10%	11- 12	0.480	119	8.97	4.86	0	4	20	41	66	118	148	161	173	182			
20%	13- 14	0.480	125	9.05	4.34	0	4	5	11	13	28	36	36	43	51			
30%	15- 16	0.480	124	9.12	3.84	0	2	4	5	6	20	31	24	23	27			
40%	167-168	0.480	128	9.20	3.33	8	4	8	9	12	12	11	9	10	14			
50%	201-202	0.480	132	9.28	2.81	8	8	11	10	4	8	8	1	6	14			

* ($NaOH$ added to Cement B to increase eq. Na_2O from 1.01 to 1.25%)

Table XI (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O(Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Fly Ash																		
L2																		
10%	17- 18	0.480	106	9.28	4.87	0	4	18	33	54	117	160	184	205	222			
20%	19- 20	0.480	92	9.69	4.36	0	1	3	8	9	22	25	29	34	44			
30%	21- 22	0.480	85	10.1	3.88	0	2	2	2	1	18	18	15	17	22			
40%	169-170	0.480	87	10.5	3.36	7	4	7	8	11	11	7	9	11	13			
50%	203-204	0.480	80	10.9	2.86	6	7	9	7	4	8	9	3	10	16			
S																		
10%	23- 24	0.480	112	9.76	4.83	2	3	18	36	55	113	158	185	205	222			
20%	25- 26	0.480	118	10.6	4.29	3	5	6	7	9	28	32	35	41	51			
30%	27- 28	0.480	112	11.5	3.76	1	1	3	6	5	18	22	17	19	23			
40%	171-172	0.480	121	12.4	3.22	8	7	11	12	13	14	7	9	9	12			
50%	205-206	0.480	123	13.2	2.68	7	9	12	10	8	11	12	9	16	20			
I																		
10%	29- 30	0.480	121	13.5	6.82	-5	5	41	76	111	193	256	297	325	332			
20%	31- 32	0.480	124	18.2	8.27	-4	-3	12	24	39	72	90	110	129	147			
30%	33- 34	0.480	122	22.8	9.72	-4	-4	6	17	30	53	67	81	99	107			
40%	173-174	0.480	121	27.4	11.2	-2	-4	4	8	23	36	51	64	85	95			
50%	207-208	0.480	140	32.0	12.6	6	8	14	18	25	35	48	55	78	90			

Table XI (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O (Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Fly Ash																		
E																		
10%	39- 40	0.480	118	14.6	5.09	8	15	53	98	140	213	246	258	262	268			
20%	41- 42	0.480	121	20.2	4.82	8	9	36	64	82	136	191	230	257	272			
30%	43- 44	0.480	128	25.9	4.55	4	5	24	39	51	84	117	136	162	178			
40%	175-176	0.480	127	31.5	4.28	4	2	14	21	42	61	83	103	133	149			
50%	209-210	0.480	135	37.2	4.00	12	14	27	38	50	70	96	113	149	167			
F																		
20%	233-234	0.485	129	16.6	4.40	-2	-2	1	14	25	32	50	71	100	129			
30%	235-236	0.485	130	20.5	3.92	-6	-4	4	5	11	13	25	38	54	76			
40%	237-238	0.485	133	24.4	3.43	-4	-4	3	0	5	4	9	17	25	42			
H																		
30%	239-240	0.485	128	11.7	4.18	2	5	16	25	35	47	73	107	140	169			
40%	241-242	0.485	132	12.7	3.78	4	5	16	22	30	34	53	69	93	119			
50%	243-244	0.485	133	13.6	3.38	1	1	21	26	31	36	47	57	70	93			
Slag																		
S																		
35%	45- 46	0.480	106	7.74	3.52	12	16	22	26	29	42	51	54	60	70			
50%	47- 48	0.480	106	7.25	2.72	9	14	18	19	18	24	28	26	26	33			
65%	49- 50	0.480	104	6.77	1.94	14	16	19	22	20	28	29	23	25	29			
A1																		
35%	51- 52	0.480	108	6.69	3.52	8	16	21	35	31	40	58	55	64	65			
50%	53- 54	0.480	103	5.76	2.72	10	21	23	23	23	31	35	34	35	43			
65%	55- 56	0.480	98	4.83	1.94	10	13	20	22	22	29	30	33	29	31			

Table XI (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O(Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Slag																		
A2																		
20%	245-246	0.485	114	8.28	4.43	4	5	20	30	43	64	96	115	125	138			
45%	242-248	0.485	111	7.50	3.27	7	10	17	19	20	20	21	26	29	40			
60%	249-250	0.485	117	7.30	2.57	8	11	17	20	21	20	18	22	22	32			
Condensed Silica Fume																		
S																		
5%	57- 58	0.480	93	8.66	5.15	-2	2	9	16	20	40	67	90	120	144			
10%	59- 60	0.480	75	8.45	4.94	-6	-3	2	7	7	14	22	24	35	51			
15%	61- 62	0.480	58	8.22	4.72	-7	-6	0	4	3	8	10	10	11	19			
C																		
5%	63- 64	0.480	103	9.58	5.87	2	7	14	31	44	82	112	119	128	134			
10%	65- 66	0.480	89	10.3	6.38	-3	2	6	12	12	30	54	72	89	107			
15%	67- 68	0.480	83	11.0	6.89	0	3	9	12	12	18	32	37	38	47			
Natural Pozzolan																		
Q																		
10%	69- 70	0.480	113	12.9	4.88	4	10	25	45	80	124	163	172	175	187			
20%	71- 72	0.480	114	16.8	4.40	2	8	8	13	22	30	56	67	89	96			
30%	73- 74	0.480	109	20.8	3.92	4	7	8	11	12	14	27	31	33	43			
A																		
10%	75- 76	0.480	60	8.05	4.87	8	21	28	33	36	37	40	50	53	61			
20%	77- 78	0.480	68	7.23	4.36	2	7	8	14	19	32	43	44	53	52			
30%	79- 80	0.480	94	6.38	3.87	-6	-7	-7	-5	-5	-4	0	-1	-1	0			

Table XII

ASTM C-227 Mortar Bar Expansion ($\times 10^3$)
Coarse Aggregate - Trois Rivières

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O (Kg/m^3)		Expansion ($\times 10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Controls (H.A. Cement)																		
B	81- 84	0.482	108	8.88	5.36	6	9	12	14	16	16	17	22	21	20			
"	103-106	0.482	109	8.88	5.36	4	7	11	12	15	15	18	20	23	23			
"	137-140	0.482	111	8.88	5.36	6	8	12	9	13	16	18	21	21	23			
"	195-196	0.482	110	8.88	5.36	10	12	18	19	22	23	21	23	21	24			
"	251-252	0.482	111	8.88	5.36	4	7	9	13	12	15	11	21	21	21			
L.A. Cement																		
K	191-192	0.490	104	3.69	1.06	6	6	10	11	15	15	14	14	11	14			
Flyash																		
L1																		
10%	85- 86	0.482	115	10.2	4.89	3	6	10	20	20	20	21	22	24	26			
20%	87- 88	0.482	116	11.5	4.41	0	3	3	4	6	7	8	8	9	11			
30%	89- 90	0.482	119	12.7	3.94	2	6	7	10	10	10	10	10	11	16			
40%	177-178	0.482	123	14.0	3.47	6	2	6	6	6	7	6	7	5	8			
50%	211-212	0.482	124	15.2	2.99	1	1	3	1	-1	1	1	-4	2	7			
D																		
10%	91- 92	0.482	110	8.97	4.86	2	10	11	16	18	19	20	17	22	22			
20%	93- 94	0.482	119	9.05	4.34	4	8	12	15	16	16	16	14	15	19			
30%	95- 96	0.482	123	9.12	3.84	1	4	10	12	12	12	9	10	10	15			
40%	179-180	0.482	128	9.20	3.33	2	-1	5	7	9	9	7	7	7	9			
50%	213-214	0.482	128	9.28	2.81	4	6	7	5	5	6	6	1	8	11			

Table XII (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Trois Rivières

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O (Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Flyash																		
L2																		
10%	97- 98	0.482	100	9.28	4.87	2	8	11	13	14	14	20	22	20	24			
20%	99-100	0.482	95	9.69	4.36	2	4	6	20	20	20	15	15	13	16			
30%	101-102	0.482	93	10.1	3.88	0	1	4	22	22	22	11	9	6	11			
40%	181-182	0.482	89	10.5	3.36	2	-1	2	3	5	6	5	4	8	10			
50%	215-216	0.482	76	10.9	2.86	0	0	3	3	1	2	2	-2	5	8			
S																		
10%	107-108	0.482	117	9.76	4.83	1	7	12	12	13	13	16	20	20	29			
20%	109-110	0.482	118	10.6	4.29	0	4	6	6	6	7	8	12	11	18			
30%	111-112	0.482	121	11.5	3.76	0	1	1	1	2	2	3	7	9	15			
40%	183-184	0.482	123	12.4	3.22	3	-1	4	4	4	8	7	6	7	9			
50%	217-218	0.482	123	13.2	2.68	0	0	0	-2	-3	-2	-1	-6	0	5			
T																		
10%	113-114	0.482	121	13.5	6.82	1	5	7	10	13	15	21	28	31	40			
20%	115-116	0.482	122	18.2	8.27	-4	-4	-3	-2	-1	-1	1	8	10	16			
30%	117-118	0.482	124	22.8	9.72	-8	-6	-6	-5	-5	-5	-2	4	2	10			
40%	185-186	0.482	120	27.4	11.2	-5	-7	-5	-7	1	2	2	3	6	9			
50%	219-220	0.482	133	32.0	12.6	0	-1	-3	-1	-1	3	2	-1	5	12			
E																		
10%	119-120	0.482	113	14.6	5.09	4	9	12	15	18	20	24	29	27	39			
20%	121-122	0.482	121	20.2	4.82	1	5	5	6	8	10	15	22	23	(Broken)			
30%	123-124	0.482	128	25.9	4.55	-1	0	0	1	3	3	9	13	16	(Broken)			
40%	187-188	0.482	131	31.5	4.28	-2	-5	-2	-6	4	6	6	7	9	13			
50%	221-222	0.482	132	37.2	4.00	-6	-6	-5	-5	-5	-3	-3	-5	2	10			

Table XII (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Trois Rivières

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O (Kg/m^3)		Expansion ($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Flyash																		
F																		
20%	253-254	0.482	125	16.6	4.40	2	1	3	4	5	9	-2	12	14	22			
30%	255-256	0.482	129	20.5	3.92	0	-3	1	5	3	7	-5	9	10	21			
40%	257-258	0.482	132	24.4	3.43	-2	-4	-1	2	0	4	-8	7	7	16			
H																		
30%	259-260	0.482	124	11.7	4.18	-5	-4	1	6	4	8	5	14	15	28			
40%	261-262	0.482	129	12.7	3.78	-7	-9	-4	-2	-2	3	-6	6	9	18			
50%	263-264	0.482	131	13.6	3.38	-9	-11	-9	-5	-6	0	-15	1	4	12			
Slag																		
S																		
35%	125-126	0.482	112	7.74	3.52	0	5	8	12	14	14	15	19	25	25			
50%	127-128	0.482	108	7.25	2.72	0	9	11	12	13	14	15	19	22	(Broken)			
65%	129-130	0.482	104	6.77	1.94	4	13	14	14	15	15	16	19	24	(Broken)			
A1																		
35%	131-132	0.482	106	6.69	3.52	1	9	12	14	17	17	19	20	22	31			
50%	133-134	0.482	104	5.76	2.72	0	8	11	12	14	14	15	15	17	25			
65%	135-136	0.482	101	4.83	1.94	2	10	11	13	14	14	14	18	18	22			
A2																		
20%	265-266	0.482	113	8.28	4.43	6	6	11	16	15	15	8	22	23	32			
45%	267-268	0.482	112	7.50	3.27	7	8	11	16	14	17	8	20	20	28			
60%	669-270	0.482	110	7.03	2.57	12	12	13	19	17	19	10	22	22	30			

Table XII (cont'd)

ASTM C-227 Mortar Bar Expansion ($x10^3$)
Coarse Aggregate - Trois Rivières

Mix I.D.	Bar No.	W/C+SCM	Flow, %	Eq. Na_2O(Kg/m^3)		Expansion($x10^3$)												
				Total	Soluble	14-d	28-d	2m	3m	4m	6m	9m	12m	18m	2y	3y	4y	5y
Condensed Silica Fume																		
S																		
5%	141-142	0.482	89	8.66	5.15	2	6	10	7	12	12	17	23	23	25			
10%	143-144	0.482	75	8.45	4.94	-2	6	8	3	6	14	16	32	23	28			
15%	145-146	0.482	64	8.32	4.72	-6	-2	2	-3	1	6	10	16	16	22			
C																		
5%	147-148	0.482	97	9.58	5.87	-1	6	10	7	11	15	19	24	24	27			
10%	149-150	0.482	91	10.3	6.38	-2	1	7	4	8	13	18	24	24	30			
15%	151-152	0.482	81	11.0	6.88	-5	2	4	1	7	11	17	23	21	30			
Natural Pozzolan																		
Q																		
10%	153-154	0.482	115	12.9	4.88	2	9	11	7	8	11	16	21	16	24			
20%	155-156	0.482	116	16.8	4.40	-1	4	8	4	7	8	11	15	12	19			
30%	157-158	0.482	112	20.8	3.92	-4	1	2	1	2	4	9	11	8	13			
A																		
10%	159-160	0.482	83	8.05	4.87	2	16	26	29	32	34	38	43	41	45			
20%	161-162	0.482	92	7.23	4.36	-3	4	11	18	19	28	39	47	50	55			
30%	163-164	0.482	100	6.38	3.87	-9	-10	-9	-9	-8	-8	-5	-4	-4	4			

Table XIII

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Pittsburgh

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)												
Cement:		Total	Soluble	7d	14-d	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
High Alkali, B	1	3.13	1.89	4	14	31	53	68	76	94	115	127	142			
Low Alkali, K	S	1.30	0.37			4	12	18	10	7	7		16			
Fly Ash:																
L1																
10%	20	3.58	1.72	4	16	22	34	43	47	68	85	99	135			
20%	21	4.02	1.55	1	10	9	17	25	24	41	58	74	108			
30%	22	4.47	1.39	1	11	11	20	24	25	42	54	70	99			
40%	M	4.92	1.22			6	5	23	22	18	37		14			
50%	139	5.37	1.06			5	5	4	5	-1	4		13			
D																
10%	17	3.16	1.71	6	10	19	34	44	44	63	84	89	108			
20%	18	3.18	1.53	3	6	13	20	28	25	41	51	56	74			
30%	19	3.21	1.35	6	6	15	24	30	25	39	41	43	57			
40%	N	3.24	1.17			10	13	24	27	18	33		30			
50%	137	3.28	1.00			6	7	-4	1	-2	1		3			
L2																
10%	23	3.27	1.71	3	11	19	38	49	54	76	93	109	136			
20%	24	3.41	1.53	3	11	18	26	35	39	56	69	85	118			
30%	25	3.55	1.36	7	14	18	26	33	38	51	58	69	93			
40%	O	3.69	1.18			6	14	22	28	17	36		43			
50%	136	3.83	1.01			4	4	3	1	0	6		10			
S																
10%	26	3.44	1.70	5	14	21	33	45	56	69	97	114	145			
20%	27	3.74	1.51	4	11	16	22	32	39	54	68	89	123			
30%	28	4.05	1.32	2	7	9	14	22	29	40	46	64	94			
40%	P	4.36	1.13			14	17	23	26	25	44		67			
50%	138	4.67	0.95			4	2	-1	-5	-3	2		10			

Table XIII (cont'd)

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Pittsburgh

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)												
		Total	Soluble	7d	14-d	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Fly Ash:																
T																
10%	2	4.76	2.40	9	19	36	71	95	112	140	174	204	230			
20%	3	6.39	2.91	12	24	44	91	124	145	181	233	268	293			
30%	4	8.02	3.42	13	24	46	91	123	152	193	244	243	307			
40%	Q	9.65	3.93			36	80	111	133	160	247	-	295			
50%	140	11.3	4.45			28	40	56	78	134	228	-	230			
E																
10%	5	5.13	1.79	9	10	28	52	73	88	115	141	162	183			
20%	6	7.12	1.70	8	15	30	58	87	108	143	184	210	261			
30%	7	9.12	1.60	4	14	27	61	88	104	142	193	224	248			
40%	R	11.1	1.50			12	35	58	70	92	162		206			
50%	133	13.1	1.42			14	25	28	24	68	152		210			
Slag:																
S																
35%	11	2.73	1.24	4	8	16	25	28	28	36	43	49	61			
50%	12	2.56	0.97	0	2	9	15	14	14	25	24	24	32			
65%	13	2.39	0.68	4	7	9	13	15	15	24	26	26	35			
A1																
35%	29	2.37	1.24	3	2	6	12	18	23	30	35	46	62			
50%	30	2.04	0.97	9	6	8	14	18	24	30	29	34	18			
65%	31	1.70	0.68	7	6	11	11	12	17	24	19	19	27			
A2																
20%	178	2.91	1.56			11	19	28	34	45	-	65	71			
45%	179	2.64	1.15			9	15	20	24	25	-	40	47			
60%	180	2.48	0.91			10	14	18	20	21	-	30	33			

Table XIII (cont'd)

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Pittsburgh

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3) Total	Eq. Na_2O (Kg/m^3) Soluble	Expansion% ($x10^3$) 7d	14-d	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Condensed Silica Fume:																
S																
5%	8	3.05	1.82	4	12	23	37	41	47	67	102	113	141			
10%	9	2.98	1.74	0	8	19	28	31	35	54	79	97	127			
15%	10	2.90	1.67	1	1	19	30	34	34	53	71	85	108			
C																
5%	32	3.37	2.07	3	14	22	37	52	64	91	123	146	175			
10%	33	3.63	2.25	4	11	22	33	47	57	82	117	147	193			
15%	34	3.87	2.43	8	14	24	38	50	61	84	120	154	200			
Nautral Pozzolan:																
Q																
10%	14	4.53	1.72	3	6	18	34	41	48	65	84	95	112			
20%	15	5.92	1.55	1	2	9	19	22	29	40	55	70	89			
30%	16	7.32	1.38	3	6	13	22	25	27	41	51	61	58			
A																
10%	35	2.84	1.71	-1	1	1	7	9	14	27	24	32	52			
20%	36	2.54	1.53	-1	-1	-2	3	5	10	20	15	13	24			
30%	37	2.25	1.36	-2	-1	-1	1	4	8	19	7	7	14			

Table XIV

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)									
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Cement:														
High Alkali, B	38	3.13	1.89	-3	2	6	6	4	-4	-	0			
High Alkali, B	182	3.13	1.89	0	-3	-1	0	-1	-	1	3			
High Alkali, B +	183			2	1	2	2	2	-	8	10			
High Alkali, B ++	181			-1	-1	2	2	2	-	9	6			
Low Alkali, K	U			4	9	14	6	4	6	-	5			
Fly Ash:														
L1														
10%	42	3.58	1.72	2	6	3	8	11	4	-	5			
20%	43	4.02	1.55	1	5	4	8	11	4	-	5			
30%	44	4.47	1.39	1	7	5	12	11	12	-	1			
40%	A	4.92	1.22	-2	2	4	9	2	-3	-	0			
50%	144	5.37	1.06	-6	-6	-6	-12	-17	-19	-	-22			
D														
10%	45	3.16	1.71	1	2	0	7	10	8	-	2			
20%	46	3.18	1.53	6	6	6	14	14	12	-	11			
30%	47	3.21	1.35	4	4	4	11	11	11	-	10			
40%	B	3.24	1.17	-5	0	2	8	1	4	-	-1			
50%	145	3.28	1.00	-2	-4	-6	-8	-12	-15	-	-17			
L2														
10%	48	3.27	1.71	2	2	2	12	8	3	-	3			
20%	49	3.41	1.53	4	4	3	10	11	10	-	4			
30%	50	3.55	1.36	2	4	4	12	10	11	-	7			
40%	C	3.69	1.18	0	3	8	11	1	10	-	0			
50%	142	3.83	1.01	3	-3	-3	-8	-10	-11	-	-14			

Notes: + Total alkali raised by NaOH to 1.14% eq. Na_2O by mass of cement which is the same level as Cement M.
++ Total alkali raised by NaOH to 1.25% eq. Na_2O by mass of cement as required by revised CSA 23.2 - 14A

Table XIV (Cont'd)

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
Fly Ash:		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
S														
10%	39	3.44	1.70	-5	-2	-3	-2	3	-7	-	4			
20%	40	3.74	1.51	-2	2	3	6	14	2	-	3			
30%	41	4.05	1.32	1	6	6	7	7	-2	-	0			
40%	D	4.36	1.13	0	3	6	11	0	10	-	13			
50%	143	4.67	0.95	0	-3	-11	-11	-15	-17	-	-20			
T														
10%	51	4.76	2.40	1	0	1	10	12	5	-	11			
20%	52	6.39	2.91	1	0	1	8	7	11	-	13			
30%	53	8.02	3.42	0	-2	-5	-1	1	4	-	2			
40%	E	9.65	3.93	1	3	6	10	2	12	-	13			
50%	141	12.3	4.45	12	13	2	-1	2	-5	-	-6			
E														
10%	54	5.13	1.79	-1	-4	-7	2	1	3	-	5			
20%	55	7.12	1.70	1	0	-2	5	4	7	-	11			
30%	56	9.12	1.60	2	1	0	5	4	8	-	9			
40%	F	11.1	1.50	0	2	7	11	0	7	-	3			
50%	135	13.1	1.42	5	8	9	-2	2	-7	-	-6			
F														
20%	186	5.85	1.55	8	10	5	4	5	-	7	9			
30%	187	7.22	1.38	4	5	4	2	2	-	1	4			
40%	188	8.59	1.20	4	10	4	4	2	-	6	7			
H														
30%	153	4.13	1.47	3	-3	-4	-1	-3	-	-6	-4			
40%	154	4.47	1.33	2	-3	-4	0	-3	-	-7	-8			
50%	155	4.81	1.20	0	-5	-7	-6	-7	-	-13	-9			

Table XIV (Cont'd)

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Slag:														
S														
35%	57	2.73	1.24	1	-1	0	6	6	3	-	-6			
50%	58	2.56	0.97	4	5	6	11	11	10	-	1			
65%	59	2.39	0.68	6	6	8	14	13	13	-	2			
A1														
35%	60	2.37	1.24	2	2	6	9	10	11	-	3			
50%	61	2.04	0.97	3	4	6	6	10	12	-	6			
65%	62	1.70	0.68	5	5	6	7	11	13	-	8			
A2														
20%	184	2.91	1.56	5	7	1	2	2	-	4	4			
45%	185	2.64	1.15	7	8	3	4	4	-	3	5			
Condensed Silica Fume:														
S														
5%	63	3.05	1.82	0	1	3	9	8	9	-	-1			
10%	64	2.98	1.74	-2	0	2	6	3	7	-	-3			
15%	65	2.90	1.67	-4	-1	0	7	3	8	-	2			
C														
5%	66	3.37	2.07	-4	0	2	8	4	6	-	-1			
10%	67	3.63	2.25	-4	1	4	10	6	10	-	5			
15%	68	3.87	2.43	-5	-1	1	8	7	9	-	2			
Natural Pozzolan:														
Q														
10%	69	4.53	1.72	4	1	3	8	9	7	-	3			
20%	70	5.92	1.55	4	0	-1	2	3	1	-	-7			
30%	71	7.38	1.38	1	-1	0	4	1	1	-	-3			

Table XIV (Cont'd)

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Lady Evelyn Lake

Mix I.D.	Test No.	Eq. Na_2O(Kg/m^3)		Expansion% ($x10^3$)										
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
A														
10%	72	2.84	1.71	4	5	8	11	9	12		3			
20%	73	2.54	1.53	4	6	8	12	10	13		3			
30%	74	2.25	1.36	7	7	10	14	14	13		29			

Table XV

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Trois Rivieres

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Cement:														
High Alkali, B	75	3.13	1.89	1	0				1	-	-4			
High Alkali, B	176	3.13	1.89	-2	1	4	5	3	-	23	25			
High Alkali, B+	177			-3	-2	1	3	6	-	7	9			
High Alkali, B++	160			1	0	2	1	0	-	-	-5			
Low Alkali, K	T			4	12	19	12	5	2					
Fly Ash:														
L1														
10%	79	3.58	1.72	2	-3	4	8	11	8	-	0			
20%	80	4.02	1.55	5	-3	2	7	11	8	-	-4			
30%	81	4.47	1.39	2	-2	3	8	11	7	-	-2			
40%	G	4.92	1.22	0	5	9	11	7	12	-	0			
50%	148	5.37	1.06	-1	-2	-4	- 4	- 8	- 9	-	-13			
L1++														
30%	161			-1	1	4	4	2	-	-	-0			
40%	162			-1	1	4	5	2	-	-	-3			
50%	163			-2	0	3	3	1	-	-	0			
D														
10%	82	3.16	1.71	8	4	8	14	15	10	-	2			
20%	83	3.18	1.53	3	-3	1	7	8	5	-	23			
30%	84	3.21	1.35	2	-3	3	8	8	5	-	1			
40%	H	3.24	1.17	0	6	6	4	4	1	-	-11			
50%	149	3.28	1.00	-1	-1	0	-3	-6	-6	-	- 9			

Notes: + Total alkali raised by NaOH to 1.14% eq. Na_2O by mass of cement which is the same level as Cement, M.
++ Total alkali raised by NaOH to 1.25% eq. Na_2O by mass of cement as required by revised CSA 23.2 - 14A

Table XV Cont'd

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Trois Rivieres

Mix. I.D.	Test No.	Eq. Na_2O (Kg/m^3) Total	Eq. Na_2O (Kg/m^3) Soluble	Expansion% ($x10^3$) 28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Fly Ash														
L2														
10%	85	3.27	1.71	8	1	10	15	14	10	-	1			
20%	86	3.41	1.53	6	1	10	14	16	10	-	4			
30%	87	3.55	1.36	7	3	11	19	18	11	-	3			
40%	I	3.69	1.18	3	6	10	10	6	12					
50%	146	3.83	1.01	0	-1	-2	-2	-7	-8					
S														
10%	76	3.44	1.70	4	4	5	6	11	9	-	2			
20%	77	3.74	1.51	4	5	6	5	15	11	-	22			
30%	78	4.05	1.32	4	6	9	9	17	13	-	1			
40%	J	4.36	1.13	-1	6	9	11	4	12	-	6			
50%	147	4.67	0.95	-1	-1	-1	- 2	- 5	- 7	-	- 9			
T														
10%	88	4.76	2.40	5	0	8	12	14	11	-	5			
20%	89	6.39	2.91	7	3	10	19	17	14	-	33			
30%	90	8.02	3.42	6	4	10	12	15	13	-	30			
40%	K	9.65	3.93	4	7	9	14	5	13	-	3			
E														
10%	91	5.13	1.79	7	6	7	11	12	10	-	13			
20%	92	7.12	1.70	4	4	3	9	12	9	-	6			
30%	93	9.12	1.60	8	5	7	10	18	14	-	10			
40%	L	11.1	1.50	-1	2	5	8	2	8	-	-1			
50%	134	13.1	1.42	7	11	9	0	4	-8	-	-5			

Table XV Cont'd

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Trois Rivieres

Mix I. D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
Fly Ash		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
F														
20%	170	5.85	1.55	0	1	5	4	2	-	5	6			
30%	171	7.22	1.38	-2	-1	0	0	-1	-	1	0			
40%	172	8.59	1.20	1	-2	2	0	-1	-	-7	-5			
H														
30%	150	4.13	1.47	0	0	-4	-2	1	-	-4	-3			
40%	151	4.47	1.33	-4	-4	-9	-9	-1	-	-7	-7			
50%	152	4.81	1.20	4	1	7	7	2	-	-9	-4			
Slag:														
S														
35%	97	2.73	1.24	10	13	11	16	19	14	-	4			
50%	98	2.56	0.97	10	12	12	18	20	17	-	14			
65%	99	2.39	0.68	14	16	14	20	25	20	-	11			
S++														
35%	164			3	4	7	7	5	-	4	5			
50%	165			3	5	8	8	6	-	-6	-3			
65%	166			4	6	10	9	5	-	8	9			
A1														
35%	94	2.37	1.24	9	8	8	15	15	13	-	30			
50%	95	2.04	0.97	11	10	11	16	21	15	-	8			
65%	96	1.70	0.68	9	13	14	20	20	17	-	4			
A2														
20%	173	2.91	1.56	3	2	6	5	3	-	0	0			
45%	174	2.64	1.15	3	3	6	6	4	-	4	6			
60%	175	2.48	0.91	4	6	8	8	6	-	6	7			

Note + Total alkali raised by NaOH to 1.25% eq. Na_2O by mass of cement as required by revised CSA 23.2-14A

Table XV Cont'd

CSA 23.3-14A Concrete Prism Expansion ($x10^3$)
Coarse Aggregate - Trois Rivieres

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Silica Fume:														
S														
5%	103	3.05	1.82	4	8	6	14	14	9	-	1			
10%	104	2.98	1.74	7	8	10	16	19	12	-	2			
15%	105	2.90	1.67	4	3	6	8	19	12	-	2			
S+														
5%	167			3	4	8	9	7	-	-1	0			
10%	168			0	2	6	7	6	-	4	6			
15%	169			-2	2	5	4	5	-	5	4			
C														
5%	100	3.37	2.07	8	10	8	14	20	13	-	4			
10%	101	3.63	2.25	8	10	9	16	18	12	-	4			
15%	102	3.87	2.43	7	10	9	14	21	11	-	4			
Natural Pozzolan:														
Q														
10%	106	4.53	1.72	6	9	8	12	17	10	-	-1			
20%	107	5.92	1.55	4	8	6	13	14	8	-	1			
30%	108	7.32	1.38	5	8	8	13	14	13	-	6			
A														
10%	109	2.84	1.71	7	15	11	17	16	15	-	7			
20%	110	2.54	1.53	10	16	14	18	21	18	-	11			
30%	111	2.25	1.36	9	18	14	20	19	21	-	12			

Note: + Total alkali raised by NaOH to 1.25% eq. Na_2O by mass of cement as required by revised CSA 23.2-14A.

Table XV Cont'd

CSA 23.3-14A Concrete Prism Expansion* ($x10^3$)
Coarse Aggregate - Trois Rivieres

Mix I.D.	Test No.	Eq. Na_2O (Kg/m^3)		Expansion% ($x10^3$)										
		Total	Soluble	28-d	2m	3m	4m	6m	12m	18m	2y	3y	4y	5y
Fly Ash:														
L1														
0%	156	5.55	3.35	2	9	10	7	6	-					
20%	157	7.13	2.75	5	8	16	11	9	-					
30%	158	7.93	2.47	1	4	14	6	5	-					
40%	159	8.73	2.16	2	7	8	4	2	-					

* High cement factor, 550 kg/m^3

Table XVI
Rate of Expansion and Relevant Data

Mortar Bars: Lake Evelyn Lake Aggregate

Mix		Ranges		Coeff. of Corre.	Y = A + B x X		Error Estimate	
		Months	Days $^{-\frac{1}{2}}$		A	B	A	B
Cement B		1 - 6	5.29 - 12.96	.9965	-.0223	.00603	.00277	.000292
Cement K		1 - 4	5.29 - 10.58	.9923	-.00516	.00208	.00348	.000416
Fly ash L1	10%	2 - 9	7.48 - 15.87	.9864	-.0494	.00783	.00873	.000753
	20%	2 - 6	7.48 - 12.96	.9719	-.0205	.00334	.00586	.000572
	40%	.5 -24	3.74 - 25.96	.7100	.00654	.00270	.00141	.0000948
Fly ash L1	0%	1 - 9	5.29 - 15.87	.9913	-.0700	.0155	.0111	.00103
(NaOH added)	20%	2 -12	7.48 - 18.33	.9705	-.0380	.00623	.0100	.000774
	30%	2 -12	7.48 - 18.33	.9933	-.0144	.00303	.00209	.000177
	40%	1 -12	5.29 - 18.33	.9887	-.00508	.00181	.00150	.000123
Fly ash D	10%	2 - 9	7.48 - 15.87	.9917	-.102	.0161	.0140	.00121
	20%	2 - 6	7.48 - 12.96	.9702	-.0269	.00409	.00740	.000722
	30%	4 - 9	10.58 - 15.87	.9920	-.0426	.00469	.00797	.000599
	40%	.5 -24	3.74 - 25.92	.6726	.00634	.000255	.00148	.0000991
	50%	.5 -24	3.74 - 25.92	.5307	.0102	-.000262	.00207	.000158
Fly ash L2	10%	1 -12	5.29 - 18.33	.9846	-.0927	.0153	.0148	.00121
	20%	2 - 6	7.48 - 12.96	.9606	-.0232	.00356	.00704	.000687
	40%	.5 -24	3.74 - 25.96	.7384	.00523	.000271	.00130	.0000873
Fly ash S	10%	2 -12	7.48 - 18.33	.9932	-.110	.0164	.0125	.000962
	30%	4 - 9	10.58 - 15.87	.9378	-.0263	.00315	.0155	.00116
	50%	.5 -24	3.74 - 25.92	.6814	.00696	.000296	.00158	.000120
Fly ash T	10%	1 -12	5.29 - 18.33	.9949	-.131	.0238	.0132	.00108
	20%	1 -12	5.29 - 18.33	.9942	-.0541	.00907	.00535	.000440
	30%	1 - 6	5.29 - 12.96	.9863	-.0476	.00748	.00683	.000721
	40%	1 -18	5.29 - 22.45	.9963	-.0356	.00540	.00264	.000190
	50%	1 -18	5.29 - 22.45	.9951	-.0170	.00409	.00231	.000167
Fly ash E	10%	2 - 6	7.48 - 12.96	.9994	-.169	.0293	.00711	.000694
	20%	1 -12	5.29 - 18.33	.9969	-.0935	.0176	.00762	.000626
	30%	4 - 9	10.58 - 15.87	.9983	-.0794	.0124	.00958	.000719
	40%	4 -18	10.58 - 22.45	.9998	-.0388	.00768	.00135	.0000816
	50%	2 -18	7.48 - 22.45	.9995	-.0361	.00822	.00164	.000111

Y = expansion in %; X = days ; B = rate of expansion

Table XVI (cont'd)
Rate of Expansion and Relevant Data

Mortar Bars: Lake Evelyn Lake Aggregate

Mix		Ranges		Coeff. of Corre.	Y = A + B x X		Error Estimate	
		Months	Days $^{-\frac{1}{2}}$		A	B	A	B
Fly ash F	20%	2 -12	7.48 - 18.33	.9921	-.0428	.00605	.00496	.000382
	30%	3 -12	9.17 - 18.33	.9764	-.0273	.00342	.00602	.000436
	40%	3 -12	9.17 - 18.33	.9382	-.0145	.00161	.00473	.000343
Fly ash H	30%	1 -12	5.29 - 18.33	.9814	-.0416	.00752	.00801	.000659
	40%	1 -12	5.29 - 18.33	.9903	-.0208	.00470	.00359	.000295
	50%	2 -12	7.48 - 18.33	.9957	-.00398	.00325	.00195	.000151
Slag S	35%	.5 - 9	3.74 - 15.87	.9895	-.00187	.00324	.00214	.000212
Slag A1	35%	.5 - 9	3.74 - 15.87	.9770	-.00579	.00383	.00378	.000374
Slag A2	20%	1 -12	5.29 - 18.33	.9962	-.0458	.00871	.00413	.000339
Condensed Silica Fume S	5%	4 -24	10.58 - 25.92	.9981	-.0641	.00816	.00469	.000254
	10%	.5 -18	3.74 - 22.45	.9964	-.0143	.00218	.000924	.000704
	15%	.5 - 6	3.74 - 12.96	.9740	-.0135	.00168	.00172	.000196
Condensed Silica Fume C	5%	2 - 9	7.48 - 15.87	.9960	-.0786	.0121	.00725	.000626
	10%	4 -12	10.58 - 18.33	.9997	-.0707	.00780	.00182	.000124
	15%	4 -12	10.58 - 18.33	.9881	-.0246	.00342	.00555	.000377
Natural Pozzolan Q	10%	2 - 9	7.48 - 15.87	.9949	-.105	.0171	.0116	.00100
	20%	2 -18	7.48 - 22.45	.9945	-.0375	.00565	.00390	.000266
Natural Pozzolan A	20%	2 - 9	7.48 - 15.87	.9970	-.0250	.00430	.00223	.000192
	30%	.5 -24	3.74 - 25.92	.9103	-.00822	.000350	.000840	.0000563

Y = expansion in %; X = days ; B = rate of expansion

Table XVII
Rate of Expansion and Relevant Data

Concrete Prisms: Pittsburg Aggregate

Mix		Ranges		Coeff. of Corre.	Y = A + B x X		Error Estimate	
		Months	Days $^{-\frac{1}{2}}$		A	B	A	B
Cement B		.25- 6	2.65 - 12.96	.9959	-.0171	.00887	.00295	.000361
Cement K		1 -24	5.29 - 25.92	.03070	-.00776	.00219	.00438	.000304
Fly ash L1	10%	.25- 6	2.65 - 12.96	.9915	-.00863	.0056	.00273	.000333
	20%	.25- 6	2.65 - 12.96	.9679	-.00711	.00341	.00324	.000396
	30%	.25- 6	2.65 - 12.96	.9682	-.00605	.00340	.00322	.000393
	50%	1 -24	5.29 - 25.92	.5783	.000717	.000334	.00304	.000211
Fly ash D	10%	.5 -12	3.74 - 18.33	.9921	-.00644	.00508	.00307	.000288
	20%	.25- 6	2.65 - 12.96	.9799	-.00630	.00347	.00259	.000316
	30%	.5 - 6	3.74 - 12.96	.9479	-.00309	.00320	.00472	.00538
	40%	1 -12	5.29 - 18.33	.8202	.00420	.00156	.00623	.000545
Fly ash L2	10%	.25- 6	2.65 - 12.95	.9968	-.0157	.00694	.00203	.000248
	20%	.25- 6	2.65 - 12.96	.9941	-.00863	.00479	.00191	.000234
	30%	.5 - 6	3.74 - 12.96	.9937	-.00260	.00397	.00196	.000224
	40%	1 - 4	5.29 - 10.58	.9985	-.0166	.00420	.00137	.000164
	50%	1 -24	5.29 - 25.92	.7002	-.000171	.000325	.00214	.000148
Fly ash S	10%	.25-18	2.65 - 22.45	.9971	-.00714	.00559	.00194	.000161
	20%	.5 - 6	3.74 - 12.96	.9871	-.00893	.00462	.00329	.000375
	30%	.5 - 6	3.74 - 12.96	.9804	-.00987	.00366	.00323	.000368
	40%	1 -24	5.29 - 25.92	.9866	-.00210	.00257	.00274	.000190
	50%	1 -24	5.29 - 25.92	.5450	-.00357	.000379	.00376	.000260
Fly ash T	10%	.25- 6	2.65 - 12.96	.9983	-.0289	.0132	.00283	.000346
	20%	.25- 6	2.65 - 12.96	.9973	-.0384	.0171	.00465	.000568
	30%	1 - 6	5.29 - 12.96	.9994	-.0539	.0192	.00375	.000396
	40%	1 -12	5.29 - 18.33	.9969	-.0396	.0157	.00707	.000619
	50%	2 -12	7.48 - 18.33	.9955	-.104	.0180	.0122	.000992
Fly ash E	10%	.5 - 6	3.74 - 12.95	.9999	-.0325	.0114	.000738	.0000842
	20%	.25- 6	2.65 - 12.96	.9947	-.0354	.0134	.00509	.000622
	30%	.5 - 6	3.74 - 12.96	.9975	-.0435	.0141	.00438	.000499
	40%	1 -12	5.29 - 18.33	.9979	-.0494	.0114	.00421	.000368
	50%	4 -12	0.58 - 18.33	.9992	-.147	.0164	.00954	.000666

Y = expansion in %; X = days ; B = rate of expansion

Table XVII (con't)
Rate of Expansion and Relevant Data

Concrete Prisms: Pittsburg Aggregate

Mix		Ranges		Coeff. of Corre.	Y = A + B x X		Error Estimate	
		Months	Days $^{-\frac{1}{2}}$		A	B	A	B
Slag S	35%	.25- 6	2.65 - 12.96	.9761	-.00183	.00304	.00248	.000303
	50%	.5 - 6	3.75 - 12.96	.9271	-.00373	.00206	.00365	.000416
	65%	.25- 6	2.65 - 12.96	.9733	-.000210	.00171	.00147	.000180
Slag A1	35%	.5 - 6	3.74 - 12.96	.9986	-.0102	.00309	.000720	.0000821
	50%	.5 - 6	3.74 - 12.96	.9932	-.00547	.00270	.00138	.000158
	65%	.5 - 6	3.74 - 12.95	.9370	-.000522	.00171	.00280	.000319
Slag A2	20%	1 - 6	5.29 - 12.96	.9986	-.0135	.00449	.00129	.000137
	45%	1 -18	5.29 - 22.45	.9803	-.00276	.00171	.00218	.000173
	60%	1 -18	5.29 - 22.45	.9722	-.00641	.00110	.00166	.000132
Condensed Silica Fume S	5%	.25-12	2.65 - 18.33	.9954	-.0115	.00605	.00238	.000237
	10%	.25-24	2.65 - 25.92	.9946	-.0129	.00512	.00265	.000188
	15%	.5 - 6	3.74 - 12.96	.9595	-.0116	.00489	.00630	.000717
Condensed Silica Fume C	5%	.25-24	2.65 - 25.92	.9975	-.0146	.00737	.00261	.000185
	10%	.25-24	2.65 - 25.92	.9958	-.0216	.00784	.00359	.000255
	15%	.25-24	2.65 - 25.92	.9956	-.0194	.00798	.00375	.000267
Natural Pozzolan Q	10%	.5 - 6	3.74 - 25.92	.9961	-.0153	.00737	.00241	.000275
	20%	.5 -24	3.74 - 25.92	.9972	-.0109	.00374	.00157	.000106
	30%	.25- 6	2.65 - 12.96	.9885	-.00626	.00349	.00195	.000238
Natural Pozzolan A	10%	1 - 6	5.29 - 12.96	.9661	-.0178	.00323	.00422	.000499
	20%	1 - 6	5.29 - 12.96	.9750	-.0181	.00278	.00347	.000366
	30%	2 - 6	7.48 - 12.96	.9772	-.0253	.00332	.00523	.000510

Y = expansion in %; X = days ; B = rate of expansion

Table XVIII
Mortar Bar Data for Multiple Linear Regression analysis

SCM	% Replacement of Cement	Rate of Expansion ($x10^3$)	%(SiO_2+Al_2O_3 +Fe_2O_3) of SCM	Blaine (cm_2/g) of SCM	Fine Content of SCM as % < 45 μm	Pozzolan Act. of SCM		Soluble eq.Na_2O kg/m_3 Mortar Bar	Total eq. Na_2O kg/m^3 Mortar Bar	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
Fly Ash										
L1	10	7.83	89.78	3190	85.5	6.7	94	4.89	10.2	2.45
	20	3.34	89.78	3190	85.5	6.7	94	4.41	11.4	2.45
L1 * (+NaOH)	0	15.5	89.78	3190	85.5	6.7	94	7.47	11.0	2.45
	20	6.23	89.78	3190	85.5	6.7	94	6.03	13.1	2.45
	30	3.03	89.78	3190	85.5	6.7	94	5.35	14.2	2.45
	40	1.81	89.78	3190	85.5	6.7	94	4.68	15.2	2.45
D	10	16.1	87.73	2220	83.2	8.9	90	4.86	8.97	1.10
	20	4.09	87.73	2220	83.2	8.9	90	4.34	9.05	1.10
	30	4.69	87.73	2220	83.2	8.9	90	3.84	9.12	1.10
L2	10	15.3	80.98	4880	81.1	7.8	91	4.87	9.28	1.46
	20	3.56	80.98	4880	81.1	7.8	91	4.36	9.69	1.46
S	10	16.4	83.84	3600	81.0	6.9	89	4.83	9.76	2.00
	30	3.15	83.84	3600	81.0	6.9	89	3.76	11.5	2.00
T	10	23.8	68.39	6120	96.7	15.1	141	6.82	13.5	6.27
	20	9.07	68.39	6120	96.7	15.1	141	8.27	18.2	6.27
	30	7.48	68.39	6120	96.7	15.1	141	9.72	22.8	6.27
	40	5.40	68.39	6120	96.7	15.1	141	11.2	27.4	6.27
	50	4.09	68.39	6120	96.7	15.1	141	12.6	32.0	6.27

Table XVIII (cont'd)
Mortar Bar Data for Multiple Linear Regression analysis

SCM	% Replacement of Cement	Rate of Expansion ($\times 10^{-3}$)	% (SiO_2+Al_2O_3+Fe_2O_3) of SCM	Blaine (cm^2/g) of SCM	Fine Content of SCM as % < 45 μm	Pozzolan Act. of SCM		Soluble eq. Na_2O kg/m^3 Mortar Bar	Total eq. Na_2O kg/m^3 Mortar Bar	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
Fly Ash E	10	29.33	72.24	3250	80.0	6.4	95	5.09	14.6	7.45
	20	17.64	72.24	3250	80.0	6.4	95	4.82	20.2	7.45
	30	12.4	72.24	3250	80.0	6.4	95	4.55	25.9	7.45
	40	7.68	72.24	3250	80.0	6.4	95	4.28	31.5	7.45
	50	8.22	72.24	3250	80.0	6.4	95	4.00	37.2	7.45
F	20	6.05	83.41	3390	88.9	5.7	83	4.40	16.6	5.41
	30	3.42	83.41	3390	88.9	5.7	83	3.92	20.5	5.41
	40	1.61	83.41	3390	88.9	5.7	83	3.43	24.4	5.41
H	30	7.52	67.84	3700	83.9	5.8	90	4.18	11.7	2.07
	40	4.70	67.84	3700	83.9	5.8	90	3.78	12.7	2.07
	50	3.25	67.84	3700	83.9	5.8	90	3.38	13.6	2.07
Slag S	35	3.24	46.49	4280	82.9	6.9	93	3.52	7.74	0.64
A1	35	3.83	45.80	5980	98.5	10.0	114	3.52	6.69	0.30
A2	20	8.71	45.56	5260	97.0	7.9	197	4.43	8.28	0.66
Condensed Silica f S	5	8.16	95.50	43,750	98.3	12.5	119	5.15	8.66	0.51
	10	2.18	95.50	43,750	98.3	12.5	119	4.94	8.45	0.51
	15	1.68	95.50	43,750	98.3	12.5	119	4.72	8.22	0.51

Table XVIII (cont'd)
Mortar Bar Data for Multiple Linear Regression analysis

SCM	% Replacement of Cement	Rate of Expansion ($\times 10^3$)	% (SiO_2+Al_2O_3+Fe_2O_3) of SCM	Blaine (cm^2/g) of SCM	Fine Content of SCM as % < 45 µm	Pozzolan Act. of SCM		Soluble eq.Na_2O kg/m^3 Mortar Bar	Total eq. Na_2O kg/m^3 Mortar Bar	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
Condensed Silica f.										
C	5	12.1	77.41	41,700	91.1	14.2	93	5.87	9.58	2.60
	10	7.80	77.41	41,700	91.1	14.2	93	6.38	10.3	2.60
	15	3.42	77.41	41,700	91.1	14.2	93	6.89	11.0	2.60
Nat. Pozz.										
Q	10	17.1	83.94	7670	98.3	9.4	95	4.88	12.9	5.52
	20	5.65	83.94	7670	98.3	9.4	95	4.40	16.8	5.52
A	20	4.30	88.97	28,890	97.8	4.9	82	4.36	7.23	0.06
	30	3.50	88.97	28,890	97.8	4.9	82	3.87	6.38	0.06

Table XIX
Concrete Data for Multiple Linear Regression Analysis

SCM	% Replacement of Cement	Rate of Expansion ($\times 10^3$)	% (SiO_2+Al_2O_3+Fe_2O_3) of SCM	Blaine (cm^2/g) of SCM	Fine Content of SCM as % < 45 μm	Pozzolan Act. of SCM		Soluble eq.Na_2O kg/m^3 Concrete	Total eq. Na_2O kg/m^3 Concrete	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
Fly Ash										
L1	10	5.68	89.78	431900	85.5	6.7	94	1.72	3.58	2.45
	20	3.41	89.78	431900	85.5	6.7	94	1.55	4.02	2.45
	30	3.40	89.78	431900	85.5	6.7	94	1.39	4.47	2.45
D	10	5.08	87.73	2220	83.2	8.9	90	1.71	3.16	1.10
	20	3.47	87.73	2220	83.2	8.9	90	1.53	3.18	1.10
	30	3.20	87.73	2220	83.2	8.9	90	1.35	3.21	1.10
	40	1.56	87.73	2220	83.2	8.9	90	1.17	3.24	1.10
L2	10	6.94	80.98	4880	81.1	7.8	91	1.71	3.27	1.46
	20	4.79	80.98	4880	81.1	7.8	91	1.53	3.41	1.46
	30	3.97	80.98	4880	81.1	7.8	91	1.36	3.55	1.46
	40	4.20	80.98	4880	81.1	7.8	91	1.18	3.69	1.46
S	10	5.59	83.84	3600	81.0	6.9	89	1.70	3.44	2.00
	20	4.62	83.84	3600	81.0	6.9	89	1.51	3.74	2.00
	30	3.66	83.84	3600	81.0	6.9	89	1.32	4.05	2.00
	40	2.57	83.84	3600	81.0	6.9	89	1.13	4.36	2.00
T	10	13.2	68.39	6120	96.7	15.1	141	2.40	4.76	6.27
	20	17.1	68.39	6120	96.7	15.1	141	2.91	6.39	6.27
	30	19.2	68.39	6120	96.7	15.1	141	3.42	8.02	6.27
	40	15.7	68.39	6120	96.7	15.1	141	3.93	9.65	6.27
	50	18.0	68.39	6120	96.7	15.1	141	4.45	11.3	6.27

Table XIX (cont'd)
Concrete Data for Multiple Linear Regression Analysis

SCM	% Replacement of Cement	Rate of Expansion ($x10^3$)	%(SiO_2+Al_2O_3+Fe_2O_3) of SCM	Blaine (cm^2/g) of SCM	Fine Content of SCM as % < 45 μm	Pozzolan Act. of SCM		Soluble eq.Na_2O kg/m^3 Concrete	Total eq. Na_2O kg/m^3 Concrete	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
E	10	11.4	72.24	3250	80.0	6.4	95	1.79	5.13	7.45
	20	13.4	72.24	3250	80.0	6.4	95	1.70	7.12	7.45
	30	14.1	72.24	3250	80.0	6.4	95	1.60	9.12	7.45
	40	11.4	72.24	3250	80.0	6.4	95	1.50	11.1	7.45
	50	16.4	72.24	3250	80.0	6.4	95	1.42	13.1	7.45
Slag										
S	35	3.04	46.49	4280	82.9	6.9	93	1.24	2.73	0.64
	50	2.06	46.49	4280	82.9	6.9	93	0.97	2.56	0.64
	65	1.71	46.49	4280	82.9	6.9	93	0.68	2.39	0.64
A1	35	3.09	45.80	5980	98.5	10.0	114	1.24	2.37	0.30
	50	2.70	45.80	5980	98.5	10.0	114	0.97	2.04	0.30
	65	1.71	45.80	5980	98.5	10.0	114	0.68	1.70	0.30
A2	20	4.49	45.56	5260	97.0	7.9	97	1.56	2.91	0.66
	45	1.71	45.56	5260	97.0	7.9	97	1.15	2.64	0.66
	60	1.10	45.56	5260	97.0	7.9	97	0.91	2.48	0.66
Condensed Silica f.										
S	5	6.05	95.50	43,750	98.3	12.5	119	1.82	3.05	0.51
	10	5.12	95.50	43,750	98.3	12.5	119	1.74	2.98	0.51
	15	4.89	95.50	43,750	98.3	12.5	119	1.67	2.90	0.51
C	5	7.37	77.41	41,700	91.1	14.2	93	2.07	3.37	2.60
	10	7.84	77.41	41,700	91.1	14.2	93	2.25	3.63	2.60
	15	7.98	77.41	41,700	91.1	14.2	93	2.43	3.87	2.60

Table XIX (cont'd)
Concrete Data for Multiple Linear Regression Analysis

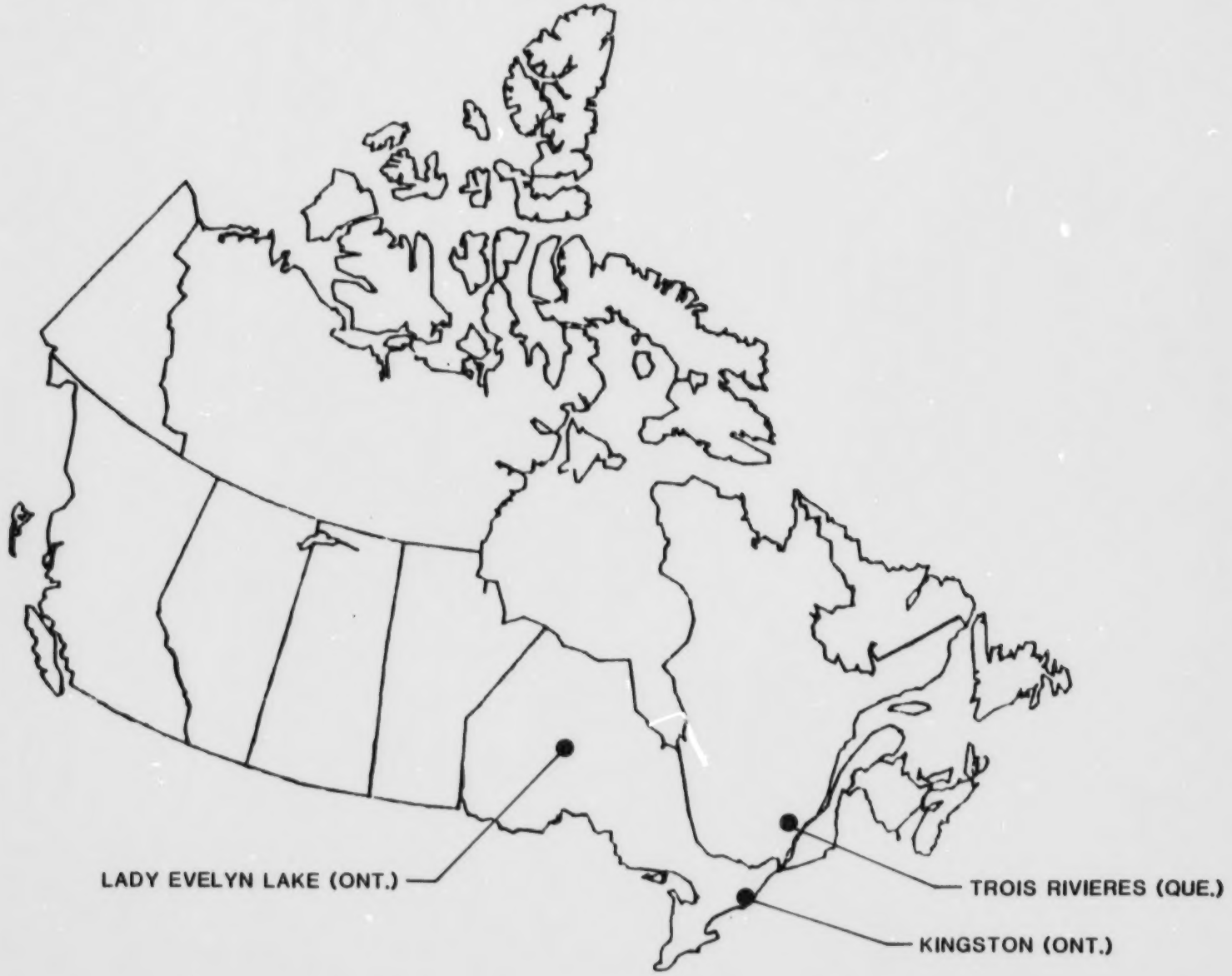
SCM	% Replacement of Cement	Rate of Expansion ($\times 10^3$)	% (SiO_2+Al_2O_3+Fe_2O_3) of SCM	Blaine (cm^2/g) of SCM	Fine Content of SCM as % < 45 μm	Pozzolan Act. of SCM		Soluble eq.Na_2O kg/m^3 Concrete	Total eq. Na_2O kg/m^3 Concrete	% Total eq. Na_2O of SCM
						with lime (MPa @ 7-d)	with cement (% @ 28-d)			
Natural Pozzolan										
Q	10	6.18	83.94	7670	98.3	9.4	95	1.72	4.53	5.52
	20	3.74	83.94	7670	98.3	9.4	95	1.55	5.92	5.52
	30	3.49	83.94	7670	98.3	9.4	95	1.38	7.32	5.52
A	10	3.23	88.97	28,890	97.8	4.9	82	1.71	2.84	0.06
	20	2.78	88.97	28,890	97.8	4.9	82	1.53	2.54	0.06
	30	3.32	88.97	28,890	97.8	4.9	82	1.36	2.25	0.06

Figure #1

LOCATION OF MINERAL ADMIXTURES

Figure #2

LOCATION OF AGGREGATE DEPOSITS



PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash Ll, N.S.

DATE April 6, 1984

Density 2.58 g/cc LIQUID A-13 Density 0.819 g/cc Viscosity 7.435 cp

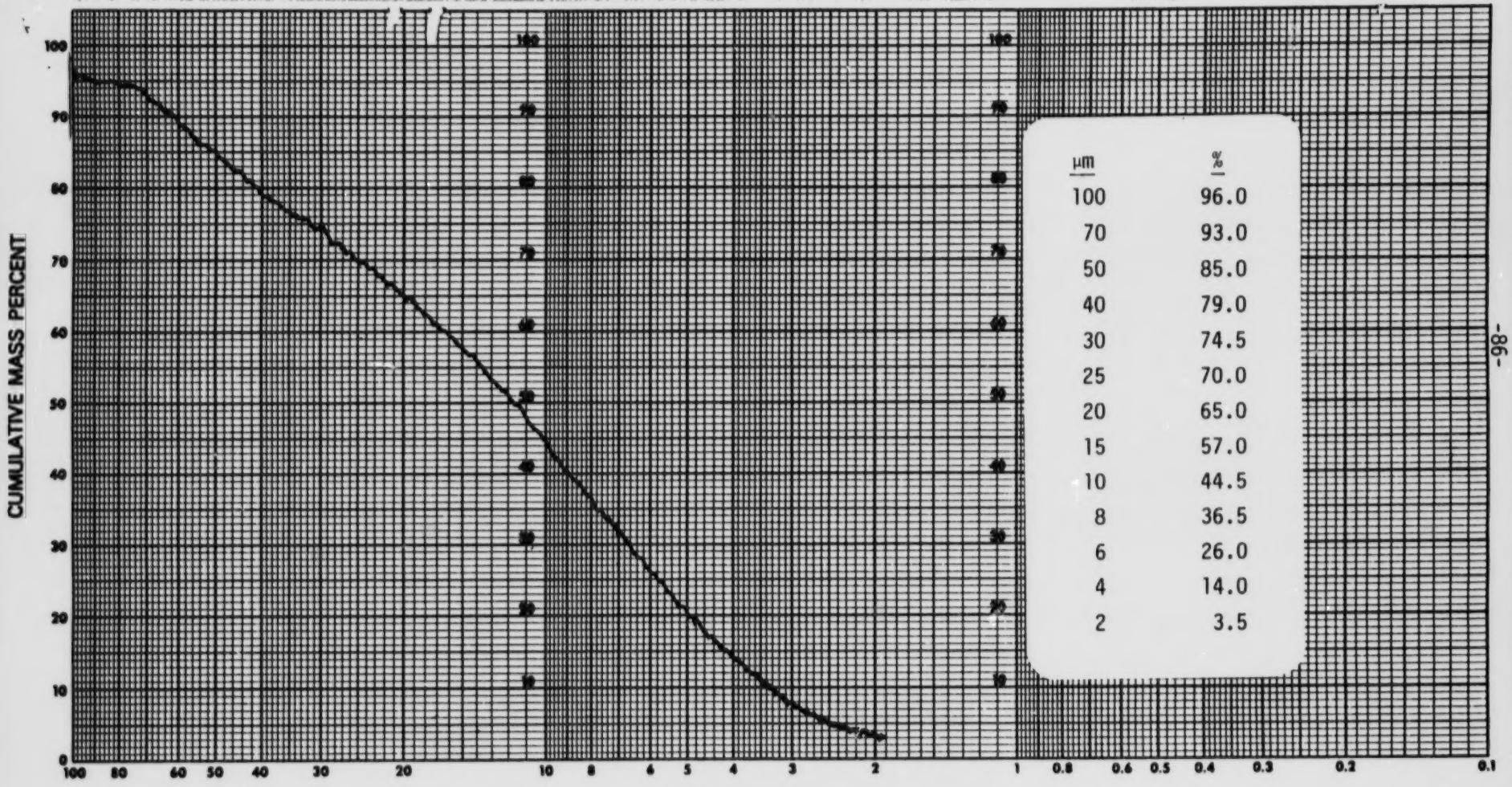
BY R. Ferguson

Preparation 4.4% Sample removed with a 106 µm sieve

TEMPERATURE 34 °C

Blaine: 319 m²/kg No. 325 Sieve: 85.5%

RATE 201 START DIA. 100 µm



µm	%
100	96.0
70	93.0
50	85.0
40	79.0
30	74.5
25	70.0
20	65.0
15	57.0
10	44.5
8	36.5
6	26.0
4	14.0
2	3.5

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Figure 3

Form 500/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash D, N.B.

DATE April 10, 1984

Density 3.01 g/cc LIQUID A-13 Density 0.821 g/cc Viscosity 8.193 cp

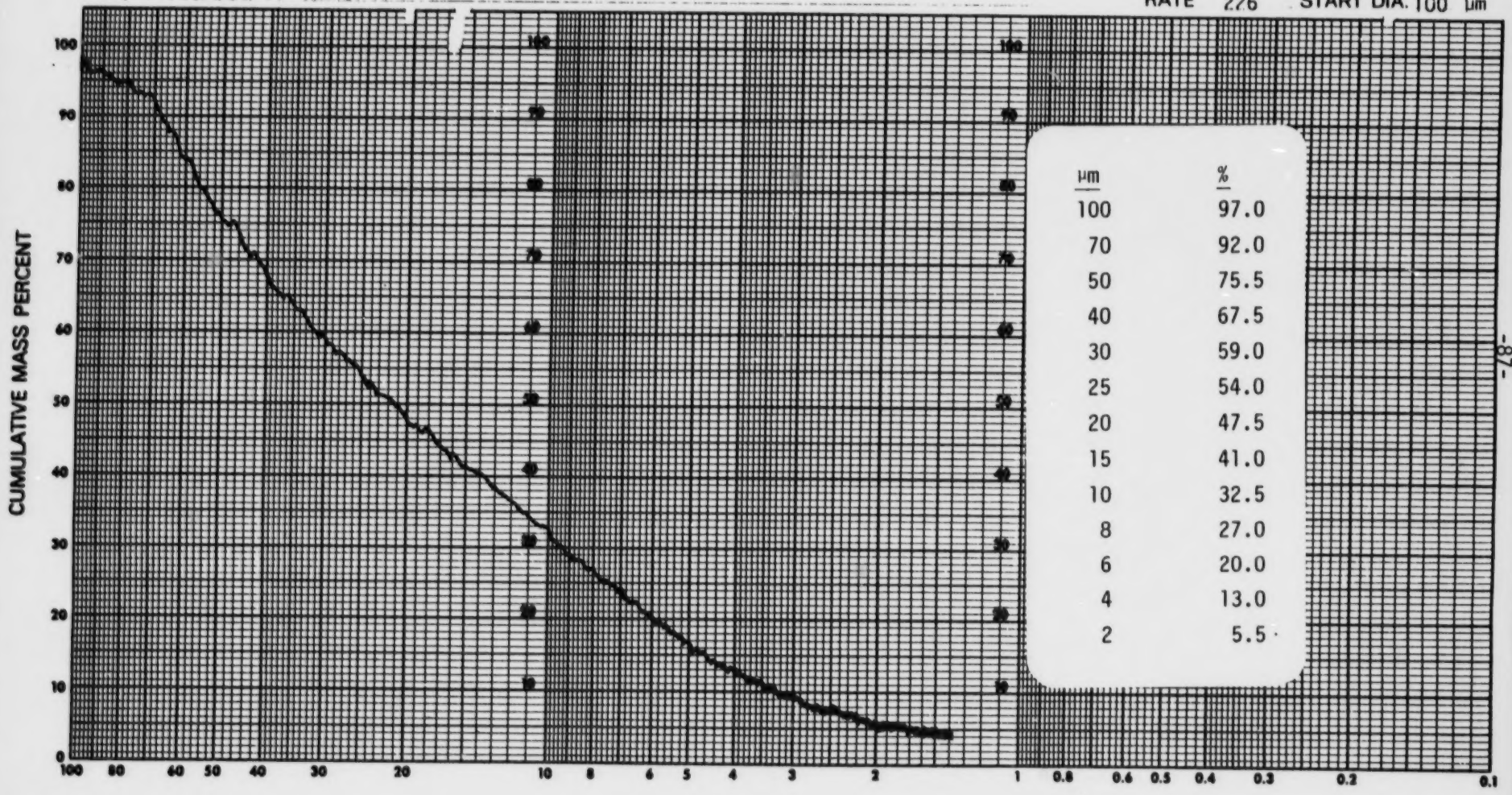
BY R. Ferguson

Preparation 3.2% Sample removed with a 106 µm sieve

TEMPERATURE 31 °C

Blaine: 222 M²/kg No. 325 Sieve: 83.2%

RATE 226 START DIA. 100 µm



µm	%
100	97.0
70	92.0
50	75.5
40	67.5
30	59.0
25	54.0
20	47.5
15	41.0
10	32.5
8	27.0
6	20.0
4	13.0
2	5.5

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Figure 4

Form 800/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash S, Alta.

DATE April 9, 1984

Density 2.14 g/cc LIQUID A-13 Density 0.818 g/cc Viscosity 6.986 cp

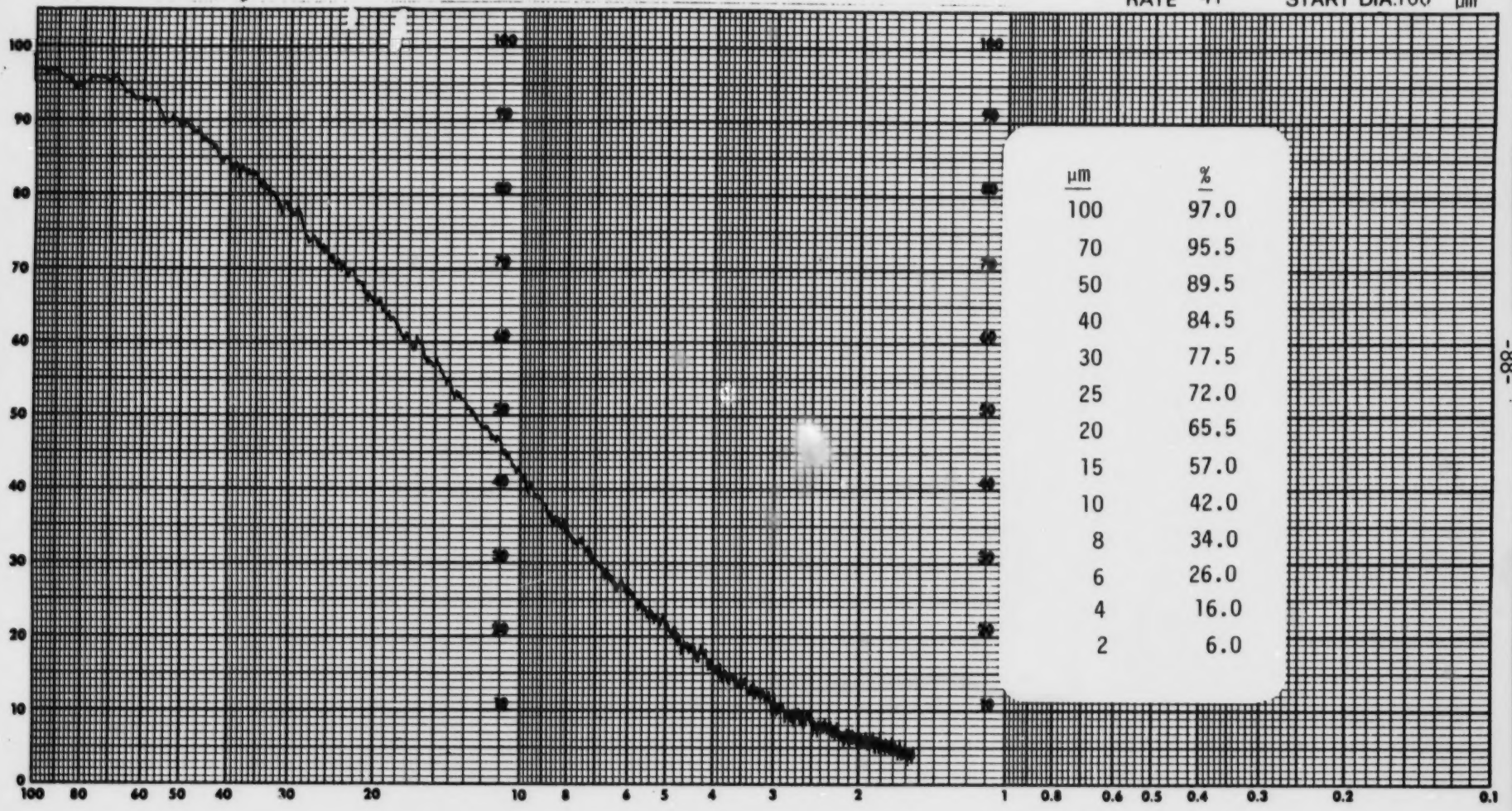
BY R. Ferguson

Preparation 3.3% Sample removed with a 106 µm sieve

TEMPERATURE 36 °C

Blaine: 360 m²/kg No. 325 Sieve: 81.7%

RATE 41 START DIA. 100 µm



µm	%
100	97.0
70	95.5
50	89.5
40	84.5
30	77.5
25	72.0
20	65.5
15	57.0
10	42.0
8	34.0
6	26.0
4	16.0
2	6.0

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Figure 5

Form 500/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash F, Alta.

DATE Jan. 17, 1985

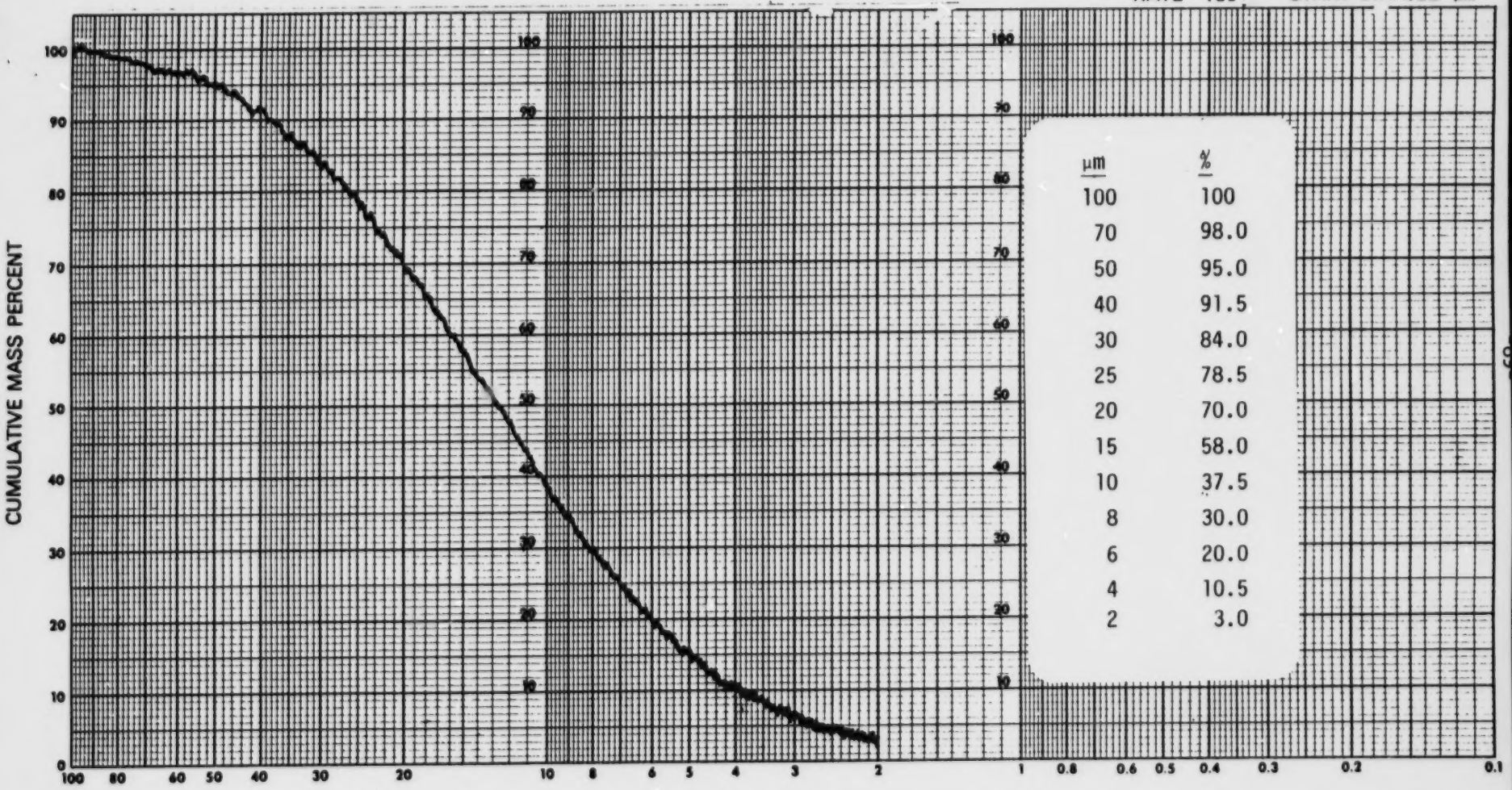
Density 1.84 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

BY R. Ferguson

Preparation

TEMPERATURE 32 °C

RATE 109 START DIA. 100 µm



µm	%
100	100
70	98.0
50	95.0
40	91.5
30	84.0
25	78.5
20	70.0
15	58.0
10	37.5
8	30.0
6	20.0
4	10.5
2	3.0

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Figure 6

Form 500/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash L2, Ont.

DATE April 9, 1984

Density 2.48 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.672 cp

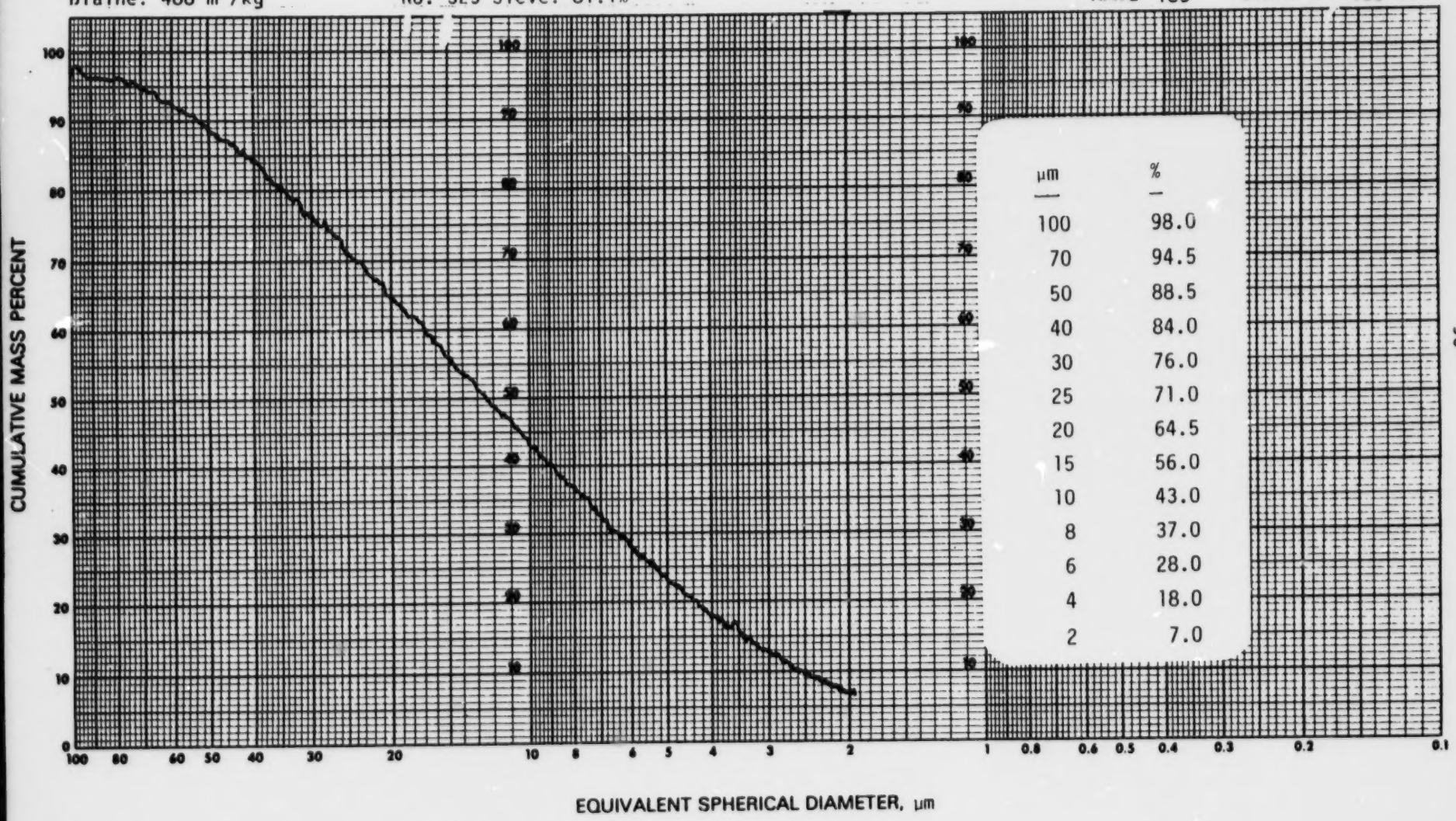
BY R. Ferguson

Preparation 3.0% Sample removed with a 106 µm sieve

TEMPERATURE 33 °C

Blaine: 488 m²/kg No. 325 Sieve: 81.1%

RATE 183 START DIA. 100 µm



µm	%
100	98.0
70	94.5
50	88.5
40	84.0
30	76.0
25	71.0
20	64.5
15	56.0
10	43.0
8	37.0
6	28.0
4	18.0
2	7.0

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Figure 7

[redacted] SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash B, Ont.

DATE May 1, 1984

Density 2.55 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

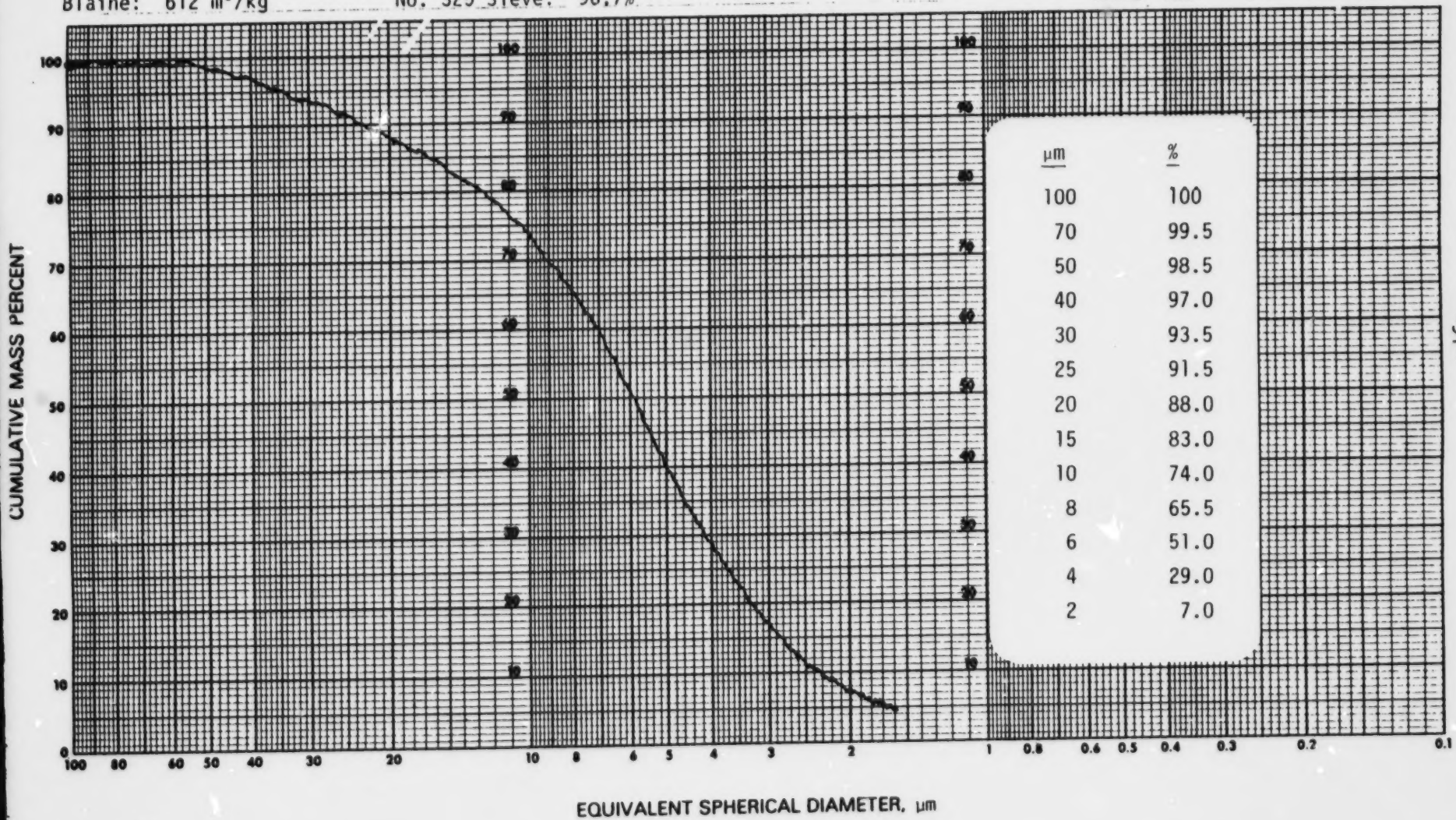
BY R. Ferguson

Preparation

TEMPERATURE 32 °C

Blaine: 612 m²/kg No. 325 Sieve: 96.7%

RATE 185 START DIA 100 µm



µm	%
100	100
70	99.5
50	98.5
40	97.0
30	93.5
25	91.5
20	88.0
15	83.0
10	74.0
8	65.5
6	51.0
4	29.0
2	7.0

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Figure 8

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash E, Sask.

DATE May 1, 1984

Density 2.45 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

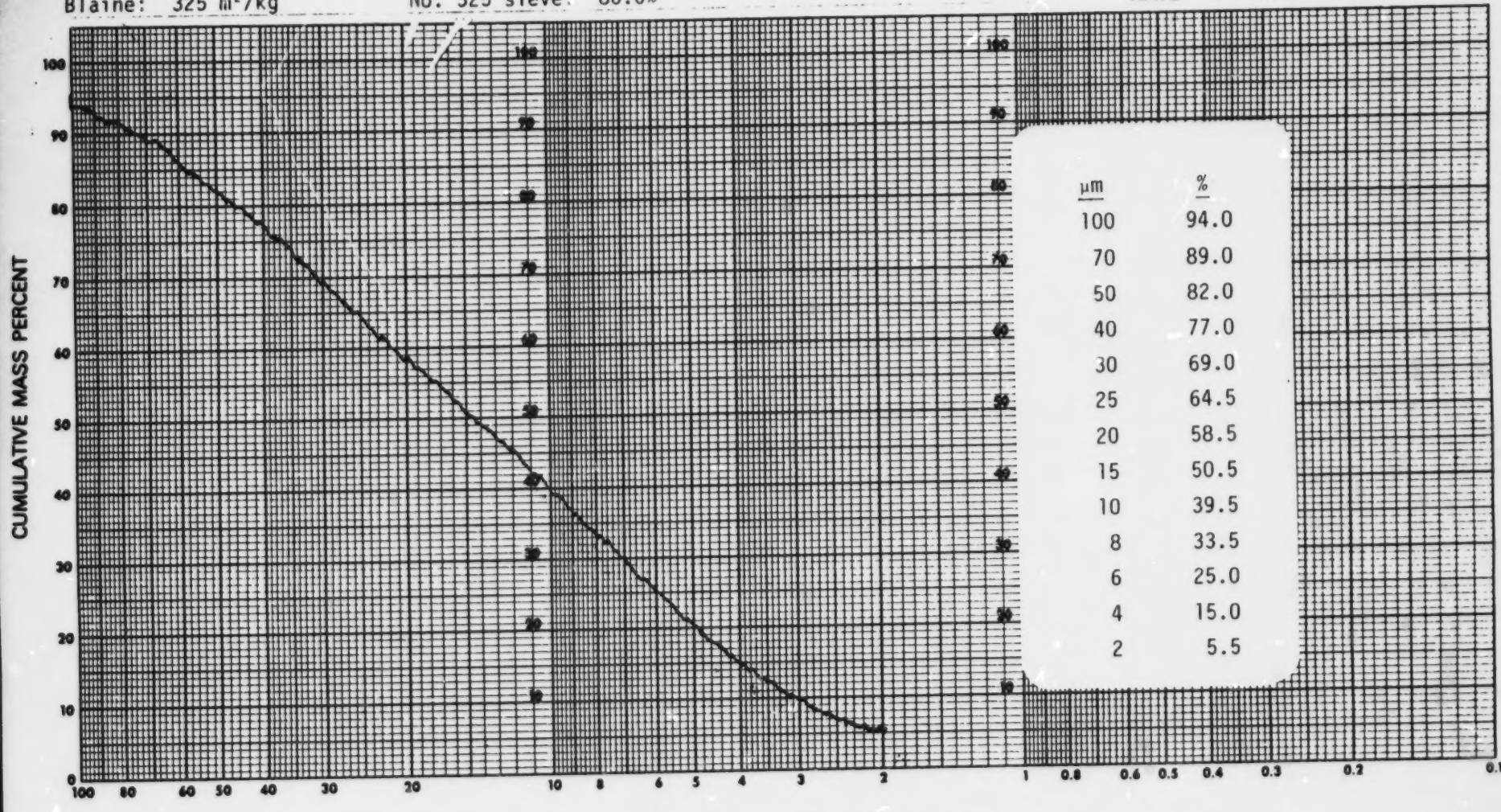
BY R. Ferguson

Preparation 5.7% Sample removed with a 106 µm sieve

TEMPERATURE 32 °C

Blaine: 325 m²/kg No. 325 sieve: 80.0%

RATE 174 START DIA. 100 µm



µm	%
100	94.0
70	89.0
50	82.0
40	77.0
30	69.0
25	64.5
20	58.5
15	50.5
10	39.5
8	33.5
6	25.0
4	15.0
2	5.5

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Figure 9

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Fly Ash H, Texas

DATE January 28, 1987

Density 2.54 g/cc LIQUID A-13 Density 0.829 g/cc Viscosity 9.089 cp

BY Claude Verville

Preparation

TEMPERATURE 30 °C

Project #20011

RATE 159 START DIA. 100 µm

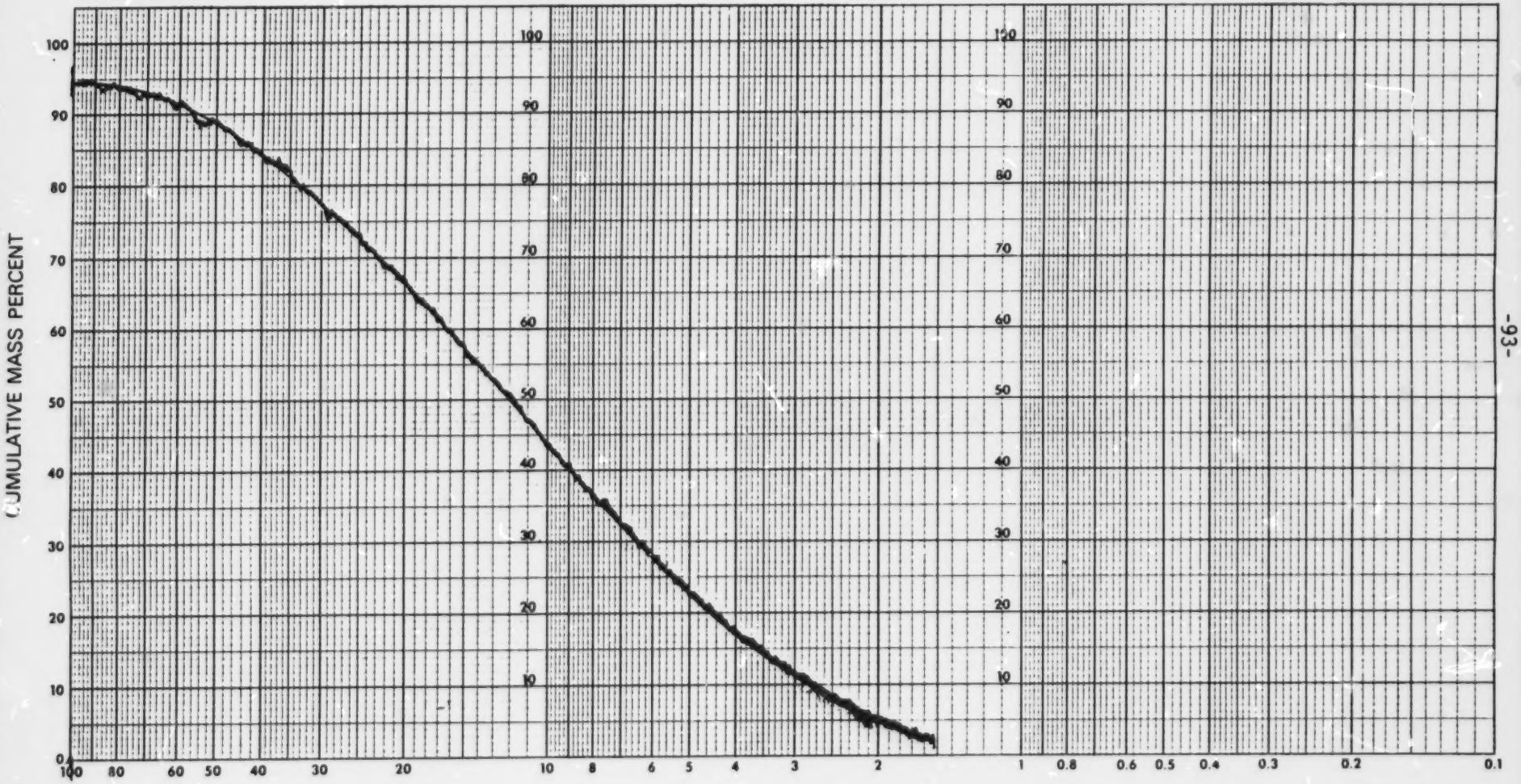

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Figure 10

Form 500/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Condensed Silica Fume S, Quebec

DATE May 8, 1984

Density 2.42 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

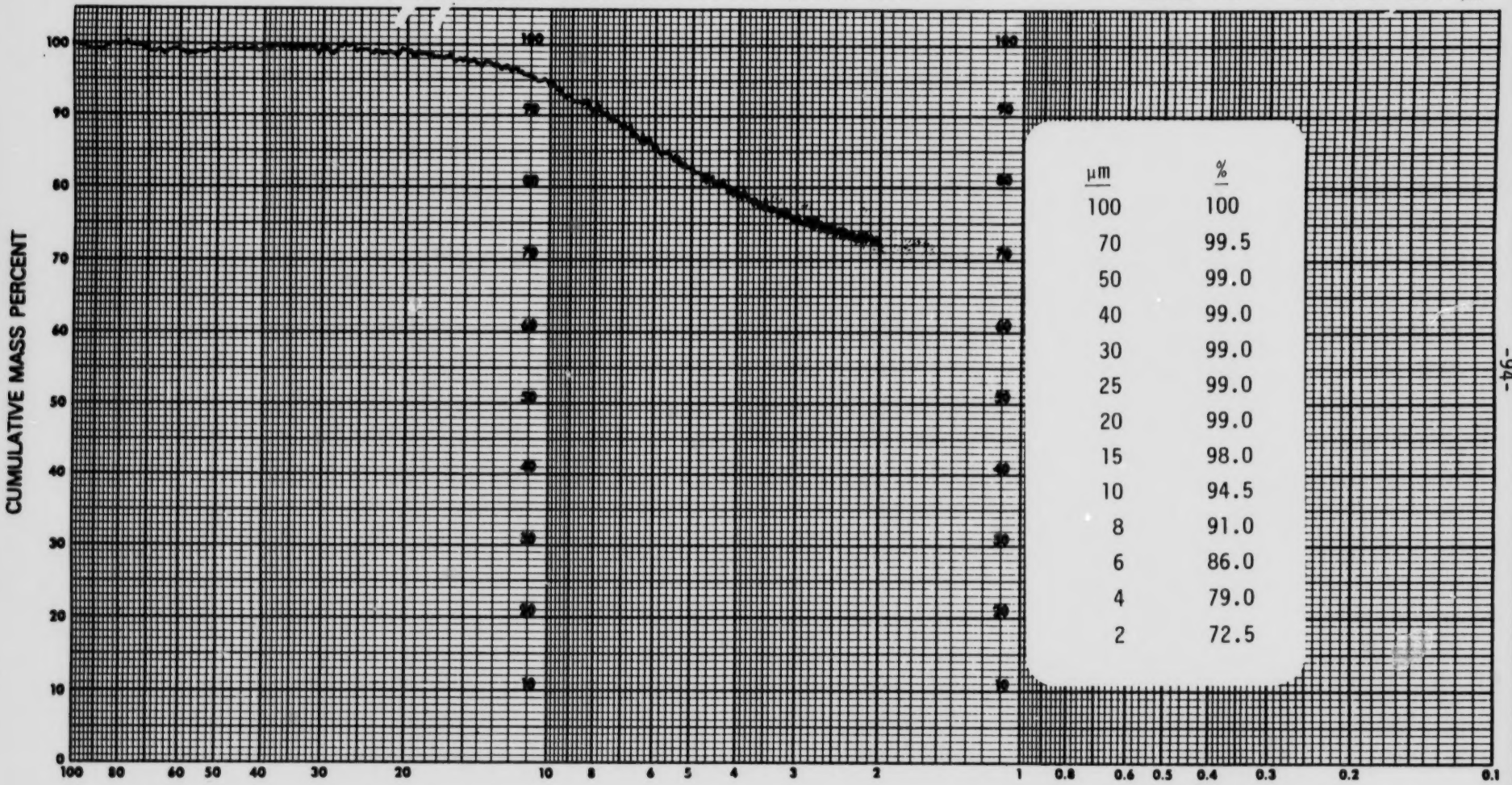
BY R. Ferguson

Preparation

TEMPERATURE 32 °C

Blaine: 4375 m²/kg No. 325 Sieve: 98.3%

RATE 171 START DIA 100 µm



µm	%
100	100
70	99.5
50	99.0
40	99.0
30	99.0
25	99.0
20	99.0
15	98.0
10	94.5
8	91.0
6	86.0
4	79.0
2	72.5

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Figure 11

Form 500/42701

SAMPLE IDENTIFICATION Condensed Silica Fume C, Quebec

DATE July 12, 1984

Density 2.48 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

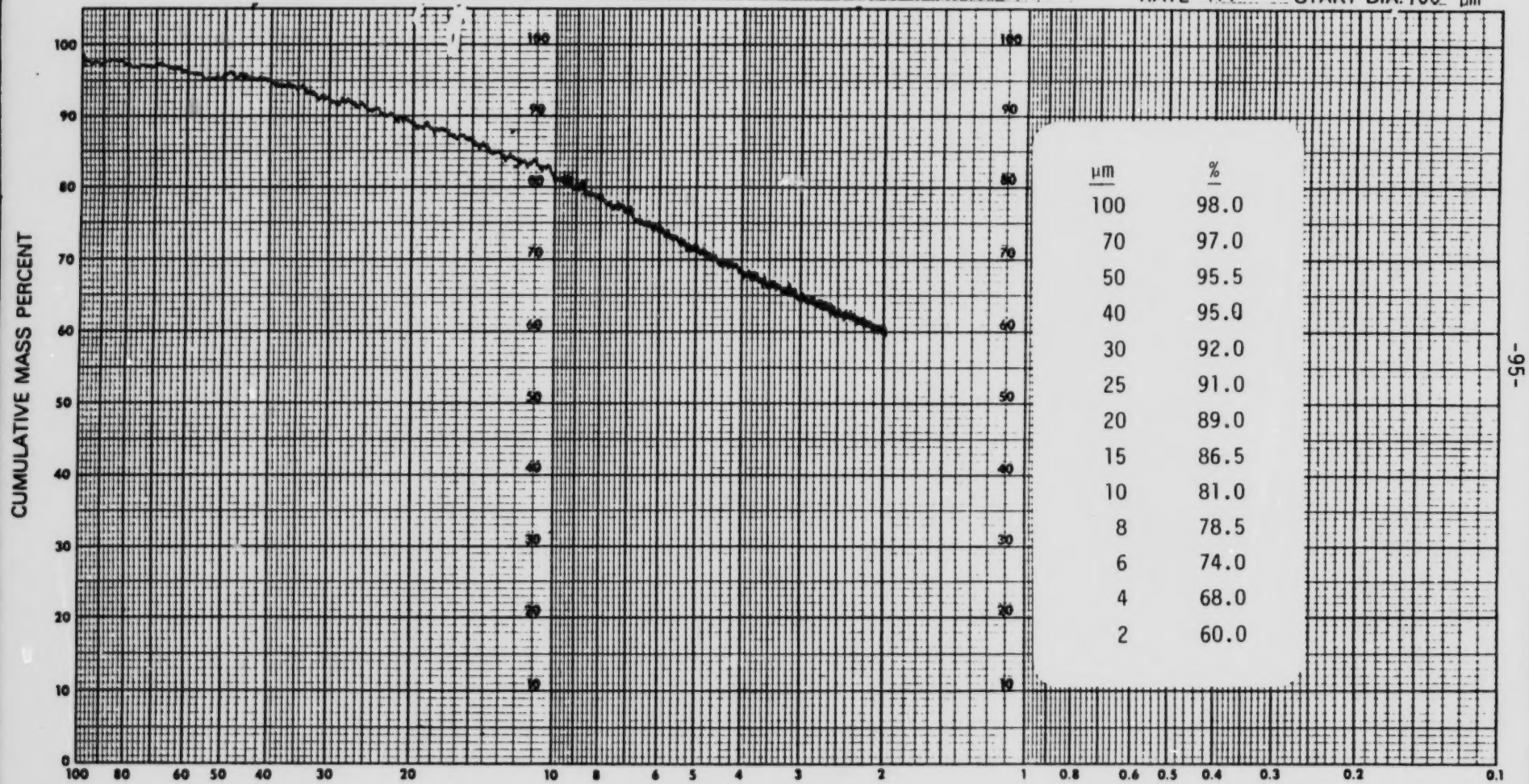
BY R. Ferguson

Preparation 2.2% Sample removed with a 106 µm sieve

TEMPERATURE 31 °C

Blaine: 4170 m²/kg No. 325 Sieve: 91.1%

RATE 177 START DIA. 100 µm



µm	%
100	98.0
70	97.0
50	95.5
40	95.0
30	92.0
25	91.0
20	89.0
15	86.5
10	81.0
8	78.5
6	74.0
4	68.0
2	60.0

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Figure 12

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Natural Pozzolan Q, B. C.

DATE May 7, 1984

Density 2.73 g/cc LIQUID A-13 Density 0.821 g/cc Viscosity 8.193 cp

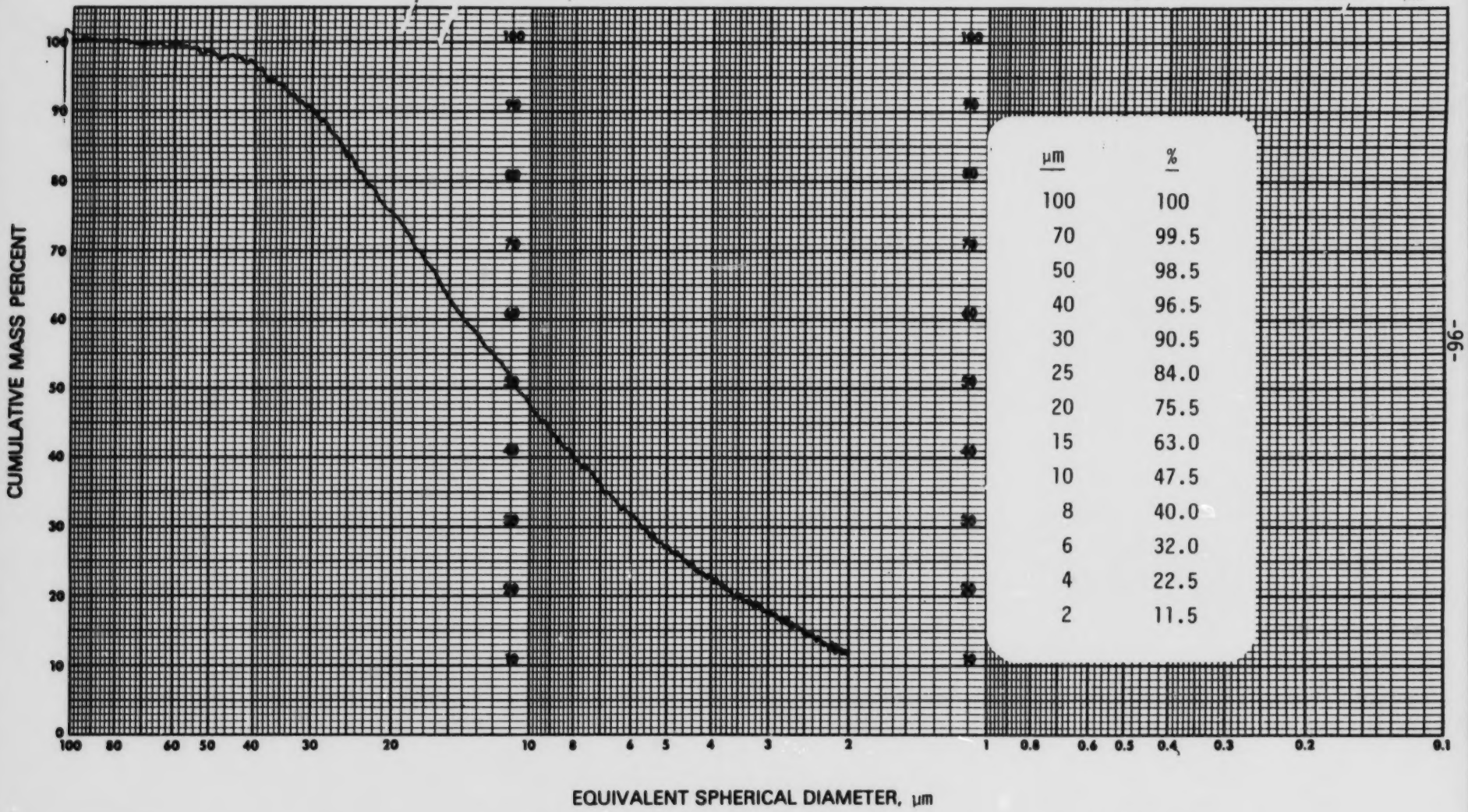
BY R. Ferguson

Preparation

TEMPERATURE 31 °C

Blaine: 767 m²/kg No. 325 Sieve: 98.3%

RATE 197 START DIA. 100 µm



µm	%
100	100
70	99.5
50	98.5
40	96.5
30	90.5
25	84.0
20	75.5
15	63.0
10	47.5
8	40.0
6	32.0
4	22.5
2	11.5

micromeritics® instrument corporation

Figure 13

Form 800/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Natural Pozzolan A, N. S.

DATE May 8, 1984

Density 2.44 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.932 cp

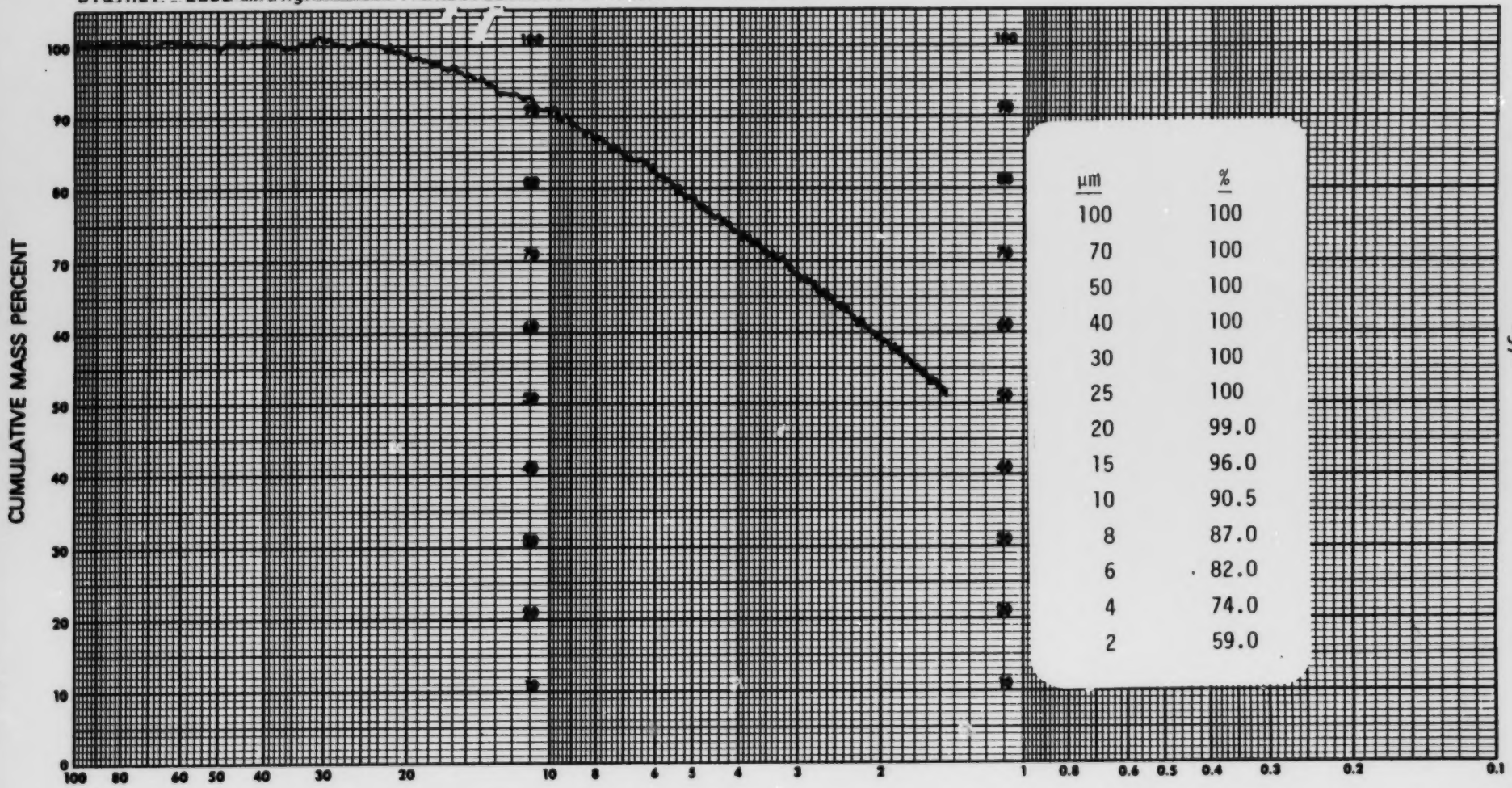
BY R. Ferguson

Preparation

TEMPERATURE 32 °C

Blaine: 2889 m²/kg No. 325 Sieve: 100%

RATE 173 START DIA. 100 µm



µm	%
100	100
70	100
50	100
40	100
30	100
25	100
20	99.0
15	96.0
10	90.5
8	87.0
6	82.0
4	74.0
2	59.0

micromeritics instrument corporation

Figure 14

Form 800/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Slag S, Ont.

DATE May 7, 1984

Density 3.00 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.682 cp

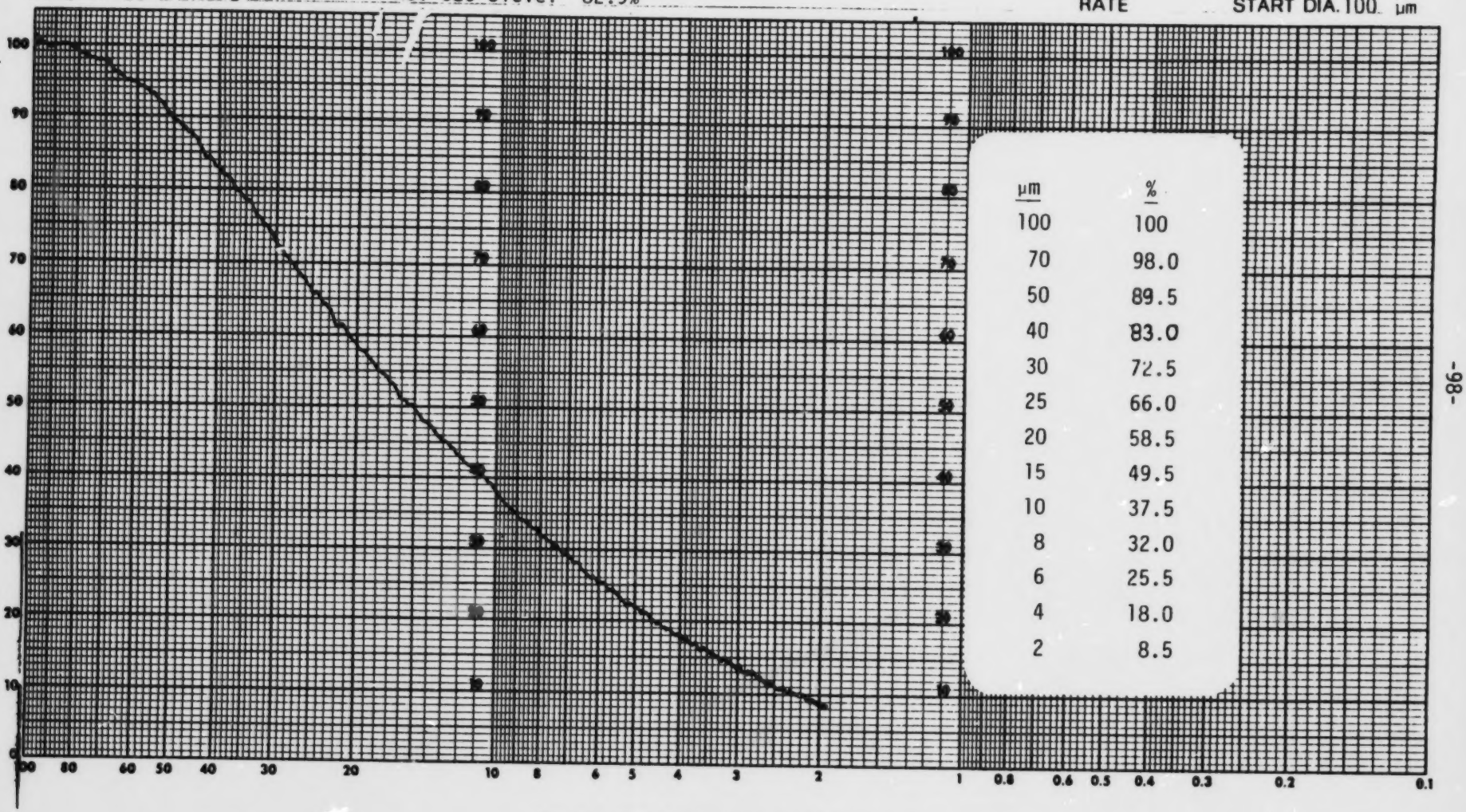
BY R. Ferguson

Preparation

TEMPERATURE 33 °C

Blaine: 428 m²/kg No. 325 Sieve: 82.9%

RATE START DIA. 100 µm



µm	%
100	100
70	98.0
50	89.5
40	83.0
30	72.5
25	66.0
20	58.5
15	49.5
10	37.5
8	32.0
6	25.5
4	18.0
2	8.5

micromeritics instrument corporation

Figure 15

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Slag A1, N. Y.

DATE May 7, 1984

Density 3.04 g/cc LIQUID A-13 Density 0.820 g/cc Viscosity 7.682 cp

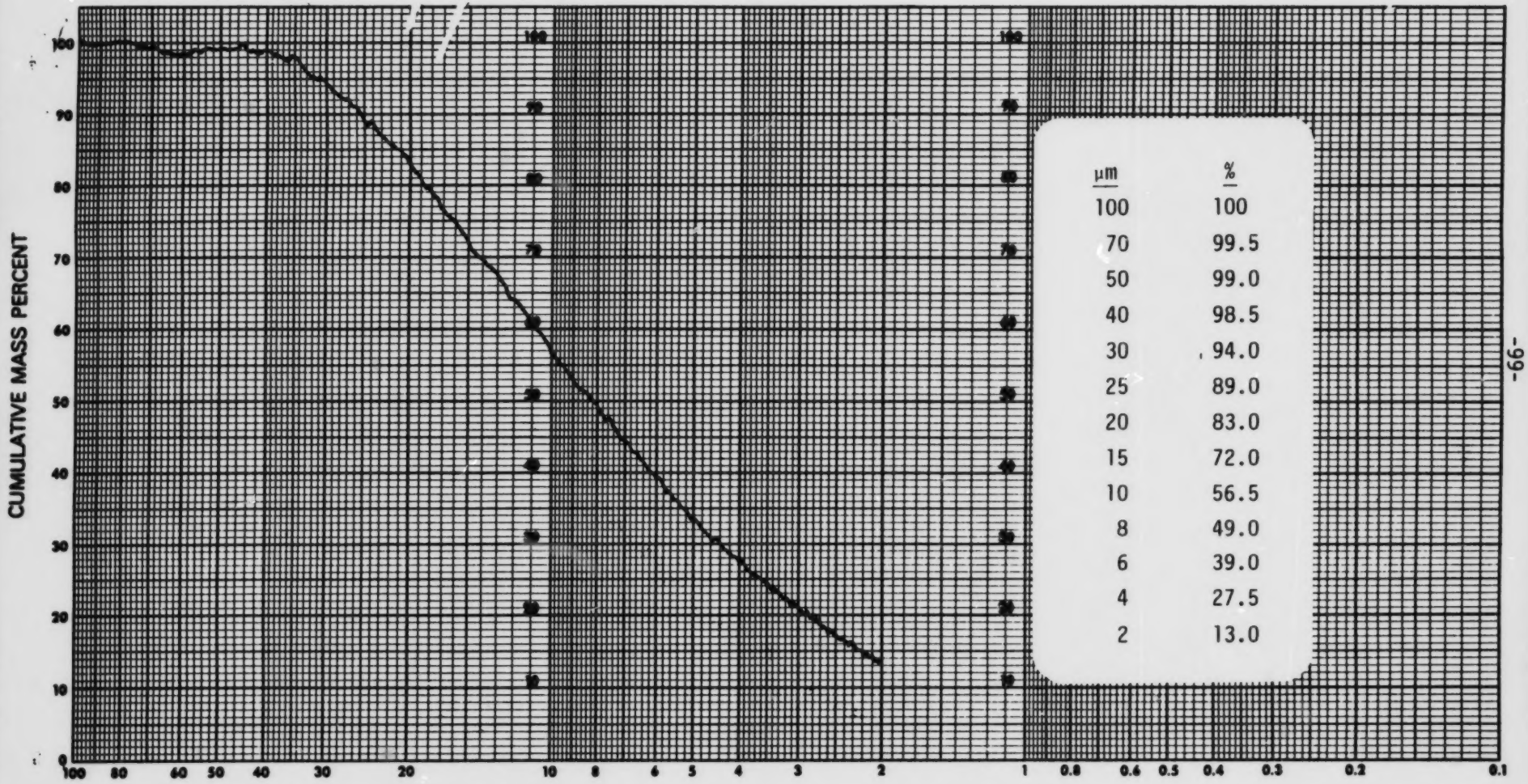
BY R. Ferguson

Preparation

TEMPERATURE 33 °C

Blaine: 598 m²/kg No. 325 Sieve: 98.5%

RATE 33 START DIA. 100 µm



µm	%
100	100
70	99.5
50	99.0
40	98.5
30	94.0
25	89.0
20	83.0
15	72.0
10	56.5
8	49.0
6	39.0
4	27.5
2	13.0

micromeritics instrument corporation

Figure 16

Form 800/42701

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Slag A2, Ont.

DATE January 28, 1987

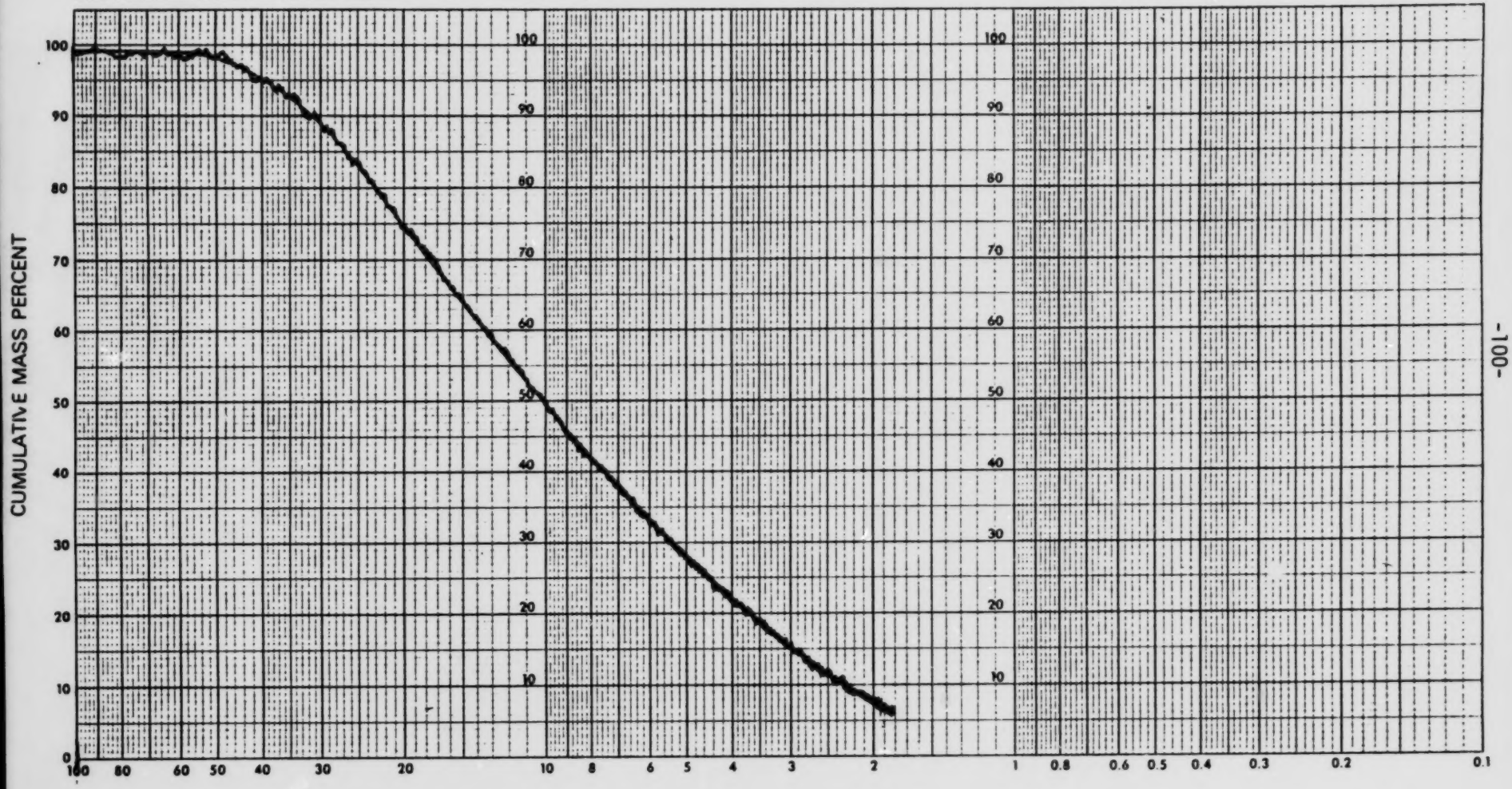
Density 2.89 g/cc LIQUID A-13 Density 0.828 g/cc Viscosity 8.891 cp

BY Claude Verville

Preparation

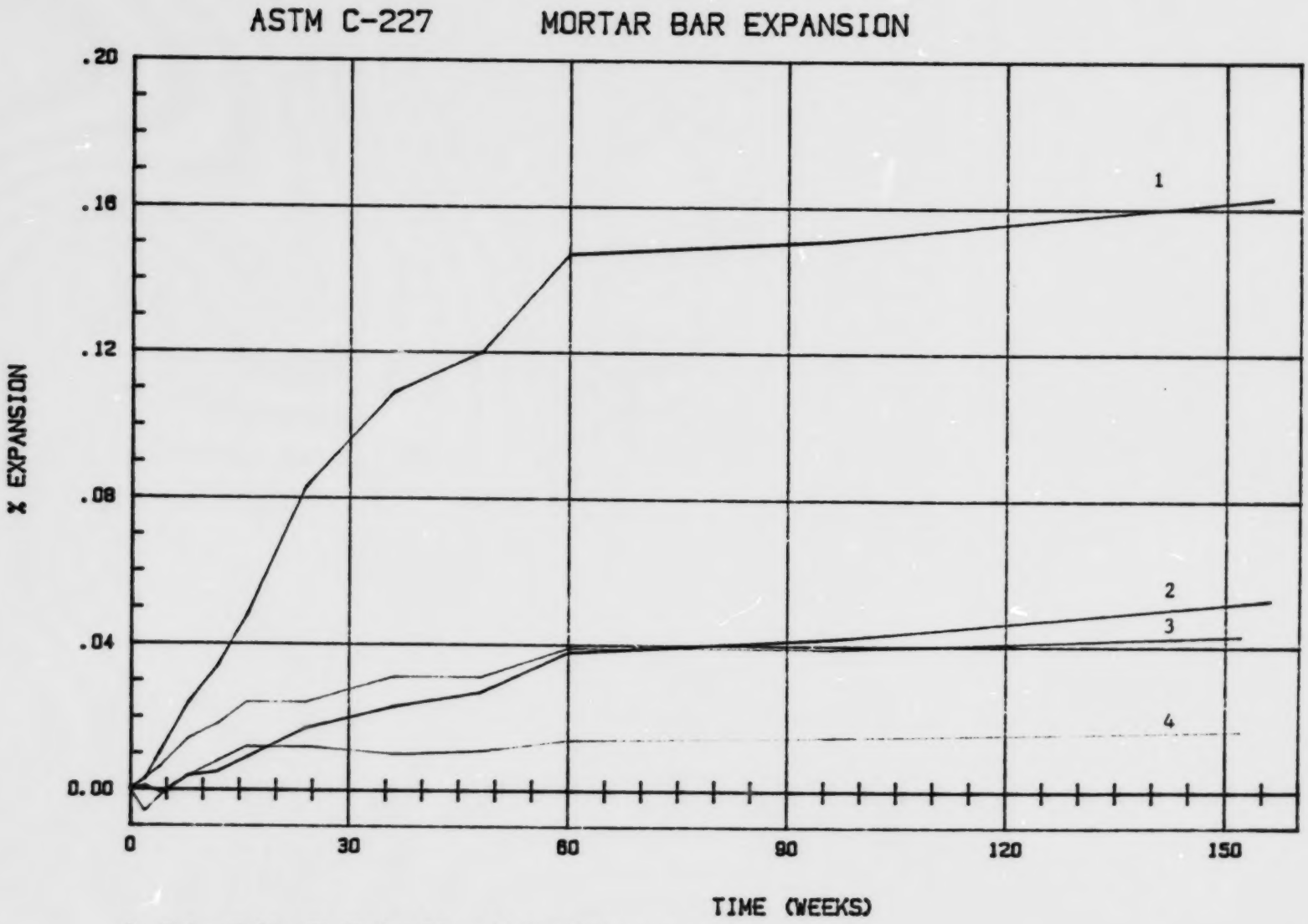
TEMPERATURE 31 °C

RATE 196 START DIA. 100 µm



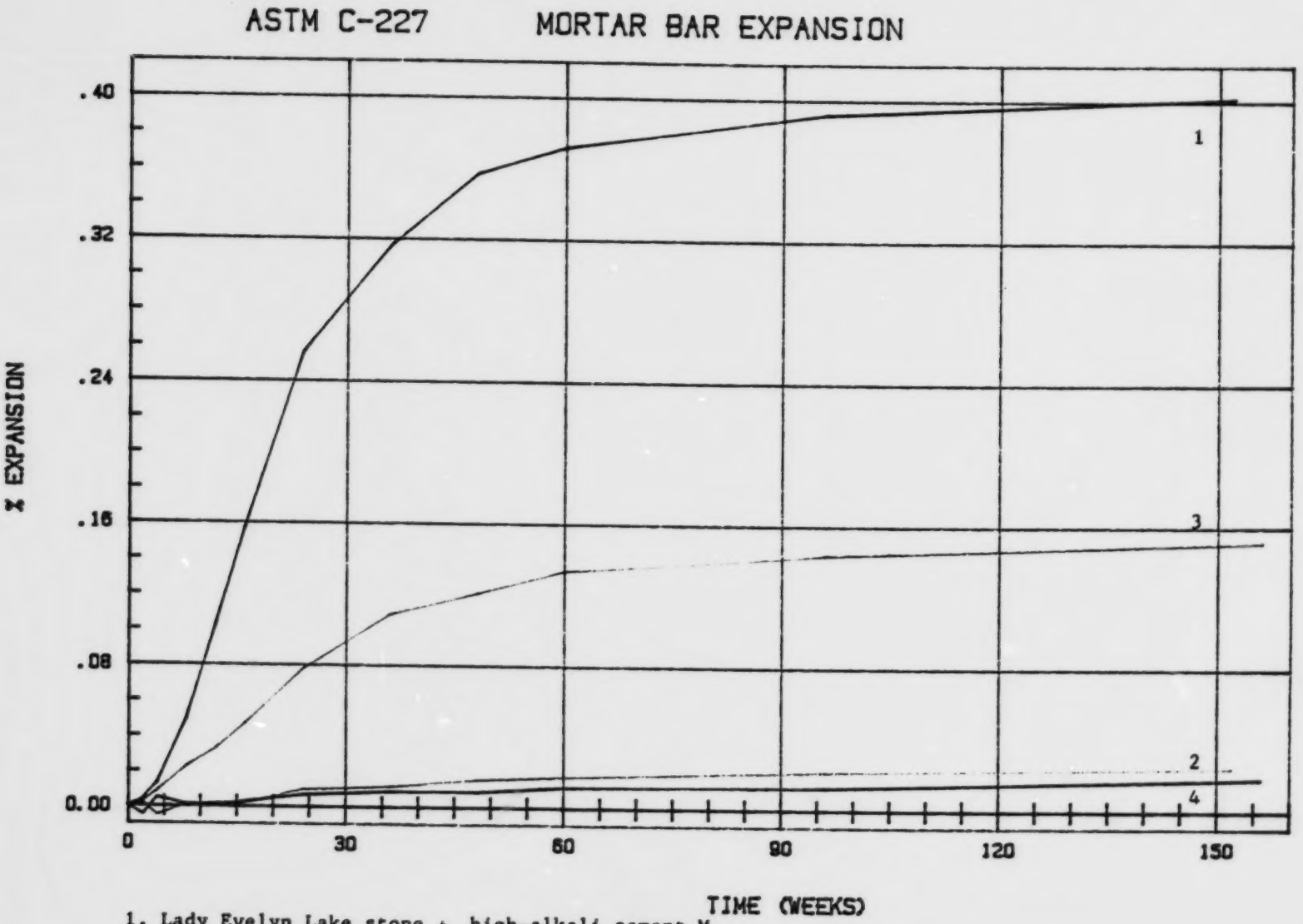
micromeritics instrument corporation

Figure 17



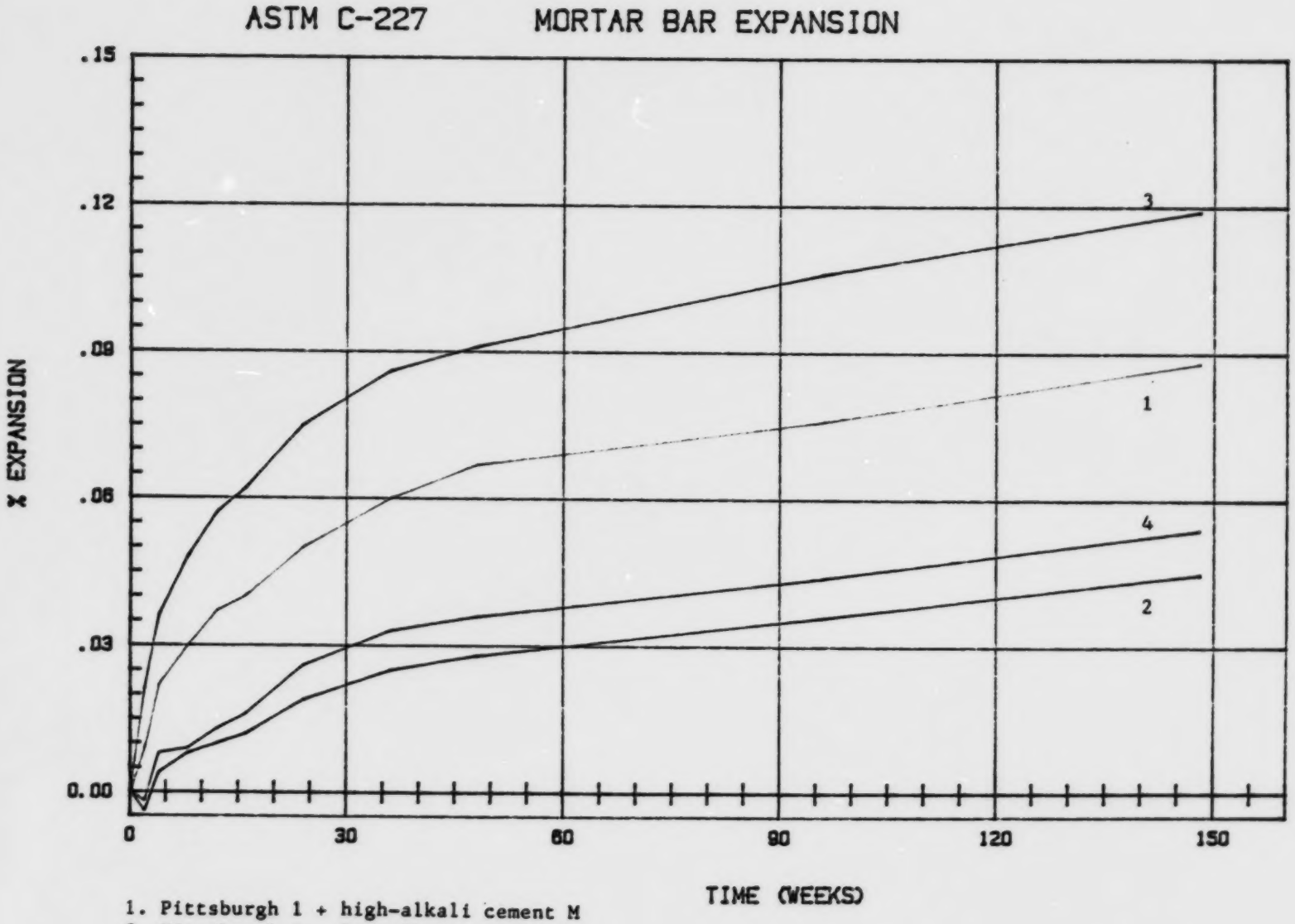
1. Nairn Falls #1 (bedrock) + high-alkali cement M
2. Nairn Falls #1 (bedrock) + low-alkali cement K
3. Nairn Falls #2 (outcrop) + high-alkali cement M
4. Nairn Falls #2 (outcrop) + low-alkali cement K

Figure 18



1. Lady Evelyn Lake stone + high-alkali cement M
2. Lady Evelyn Lake stone + low-alkali cement K
3. Trois Rivières stone + high-alkali cement M
4. Trois Rivières stone + low-alkali cement K

Figure 19



1. Pittsburgh 1 + high-alkali cement M
2. Pittsburgh 1 + low-alkali cement K
3. Pittsburgh 2 + high-alkali cement M
4. Pittsburgh 2 + low-alkali cement K

Figure 20

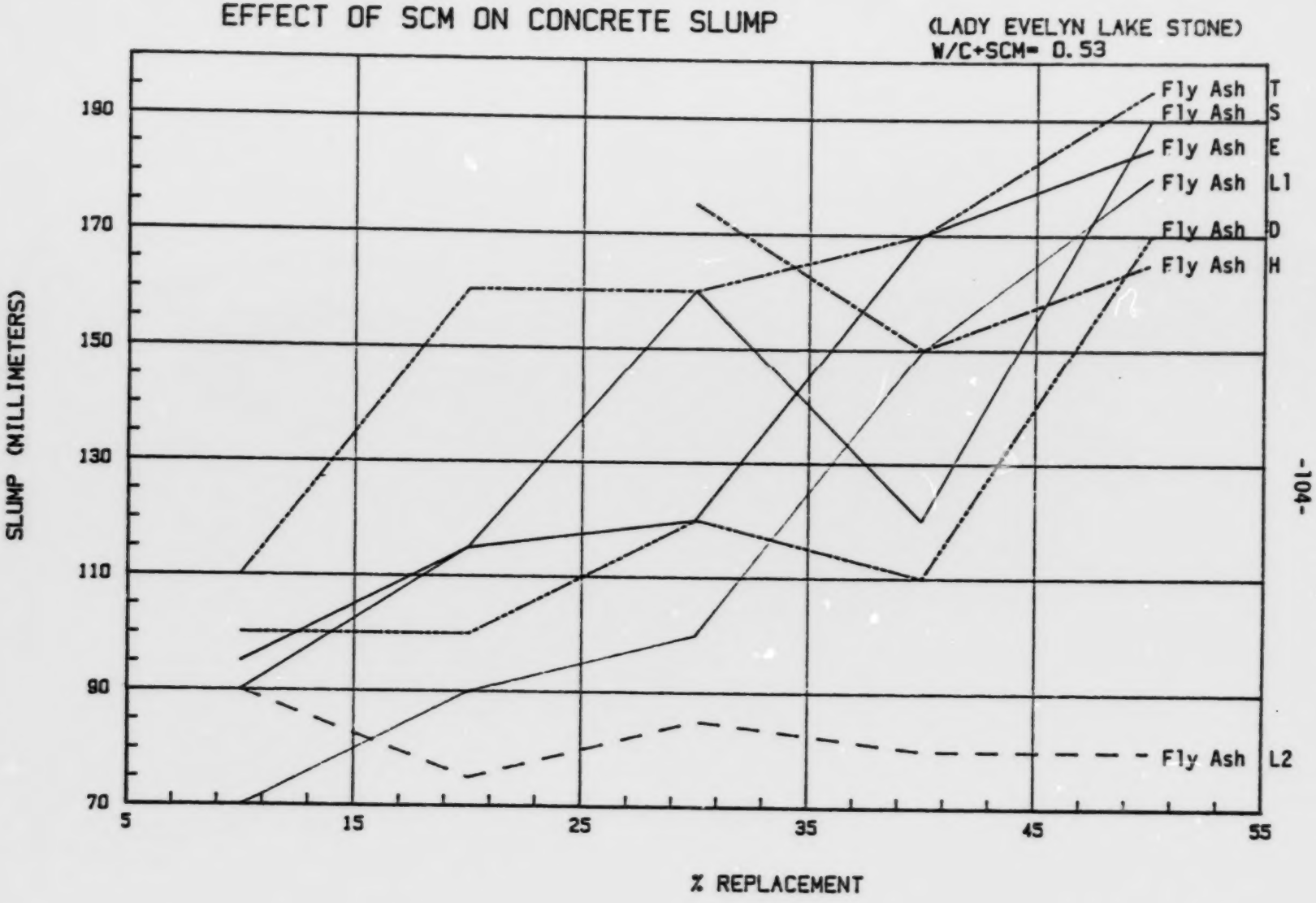

EFFECT OF SCM ON CONCRETE SLUMP
(LADY EVELYN LAKE STONE)
W/C+SCM= 0.53
SLUMP (MILLIMETERS)
190
170
150
130
110
90
70
5
15
25
35
45
55
% REPLACEMENT
Fly Ash T
Fly Ash S
Fly Ash E
Fly Ash L1
Fly Ash D
Fly Ash H
Fly Ash L2

Figure 21

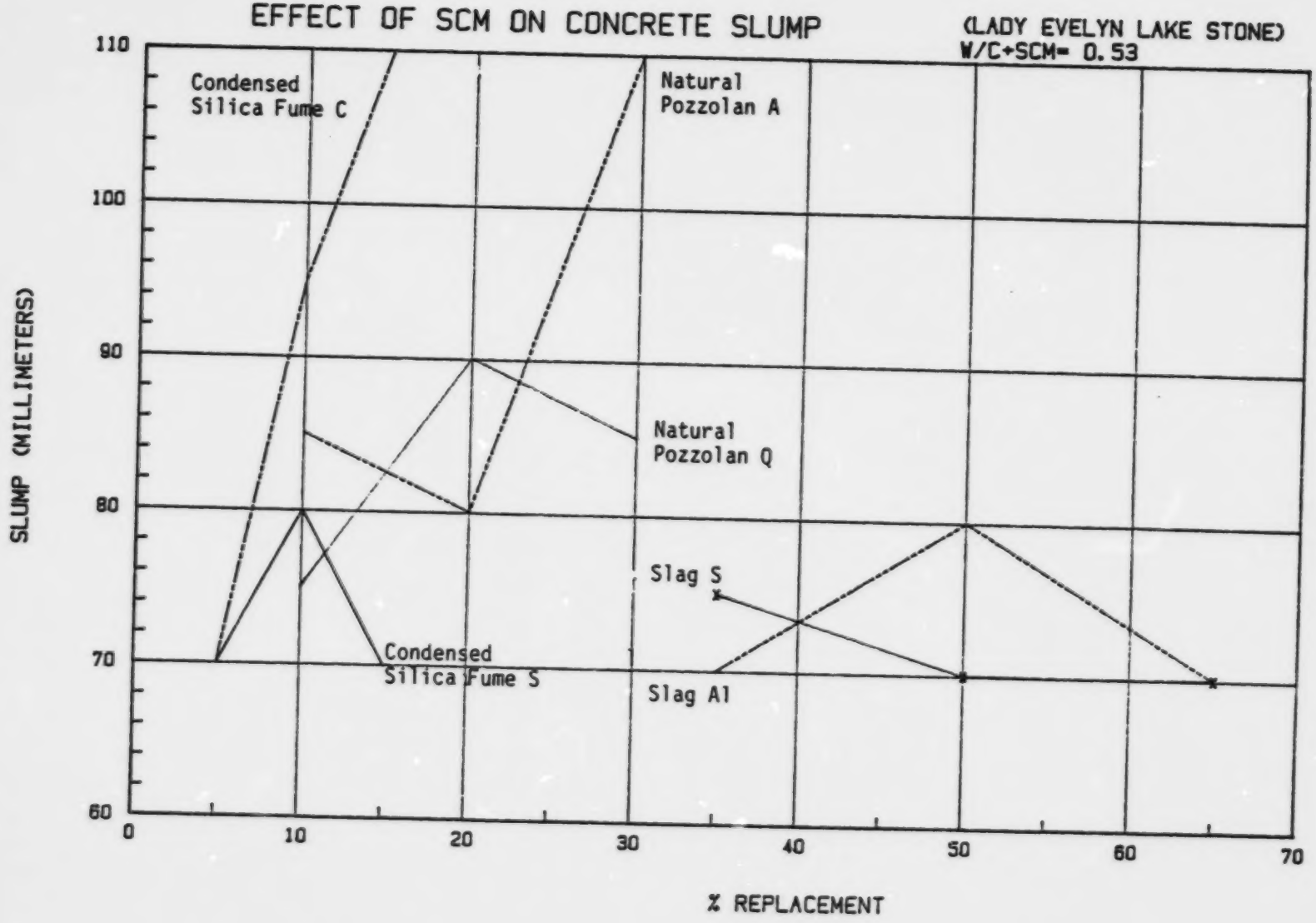

EFFECT OF SCM ON CONCRETE SLUMP
(LADY EVELYN LAKE STONE)
W/C+SCM= 0.53
SLUMP (MILLIMETERS)
110
100
90
80
70
60
0
10
20
30
40
50
60
70
% REPLACEMENT
Condensed
Silica Fume C
Natural
Pozzolan A
Natural
Pozzolan Q
Slag S
Slag A1
Condensed
Silica Fume S

Figure 22

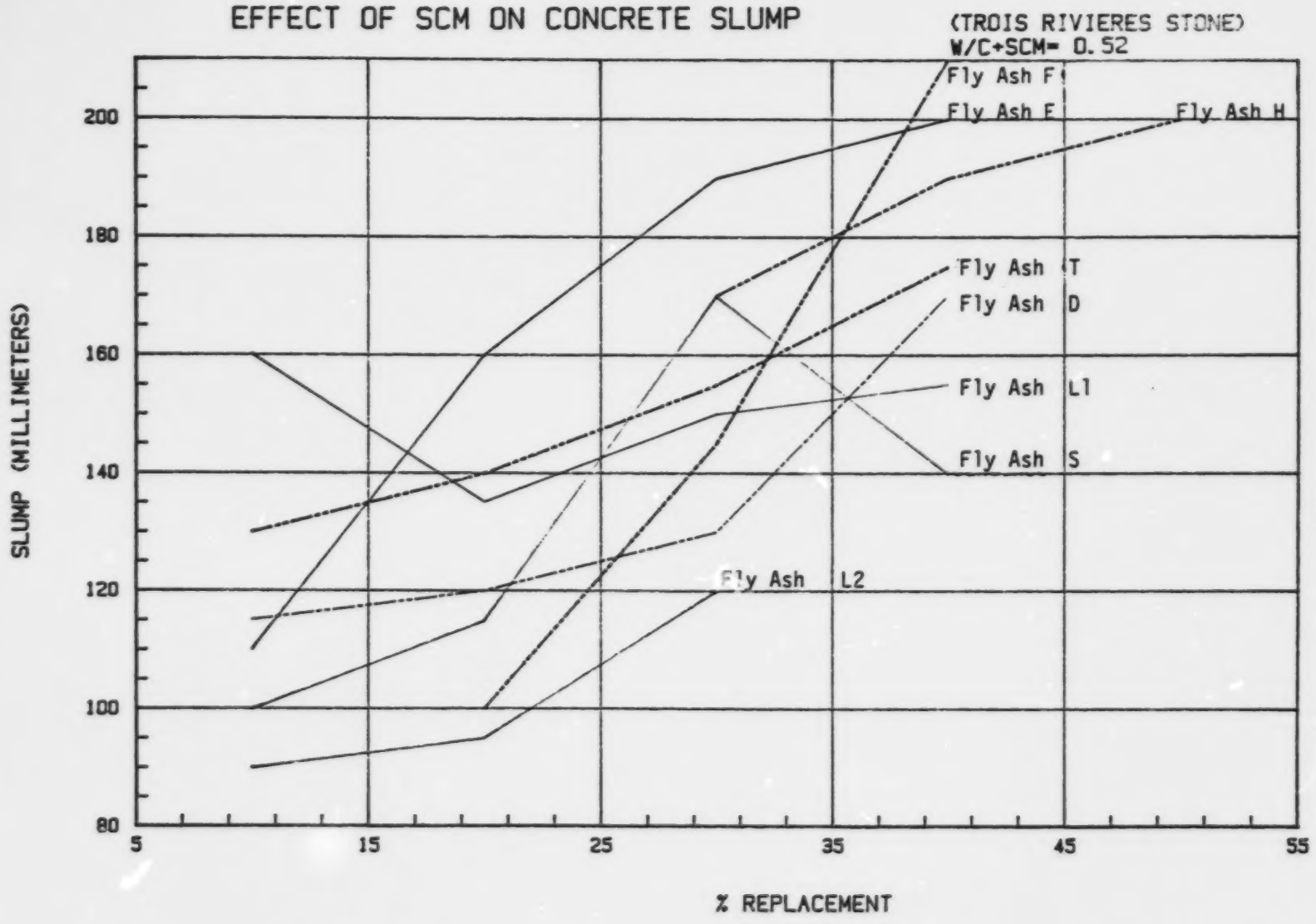

EFFECT OF SCM ON CONCRETE SLUMP
(TROIS RIVIERES STONE)
W/C+SCM= 0.52
Fly Ash F
Fly Ash E
Fly Ash H
Fly Ash T
Fly Ash D
Fly Ash L1
Fly Ash S
Fly Ash L2
SLUMP (MILLIMETERS)
200
180
160
140
120
100
80
5
15
25
35
45
55
% REPLACEMENT

Figure 23

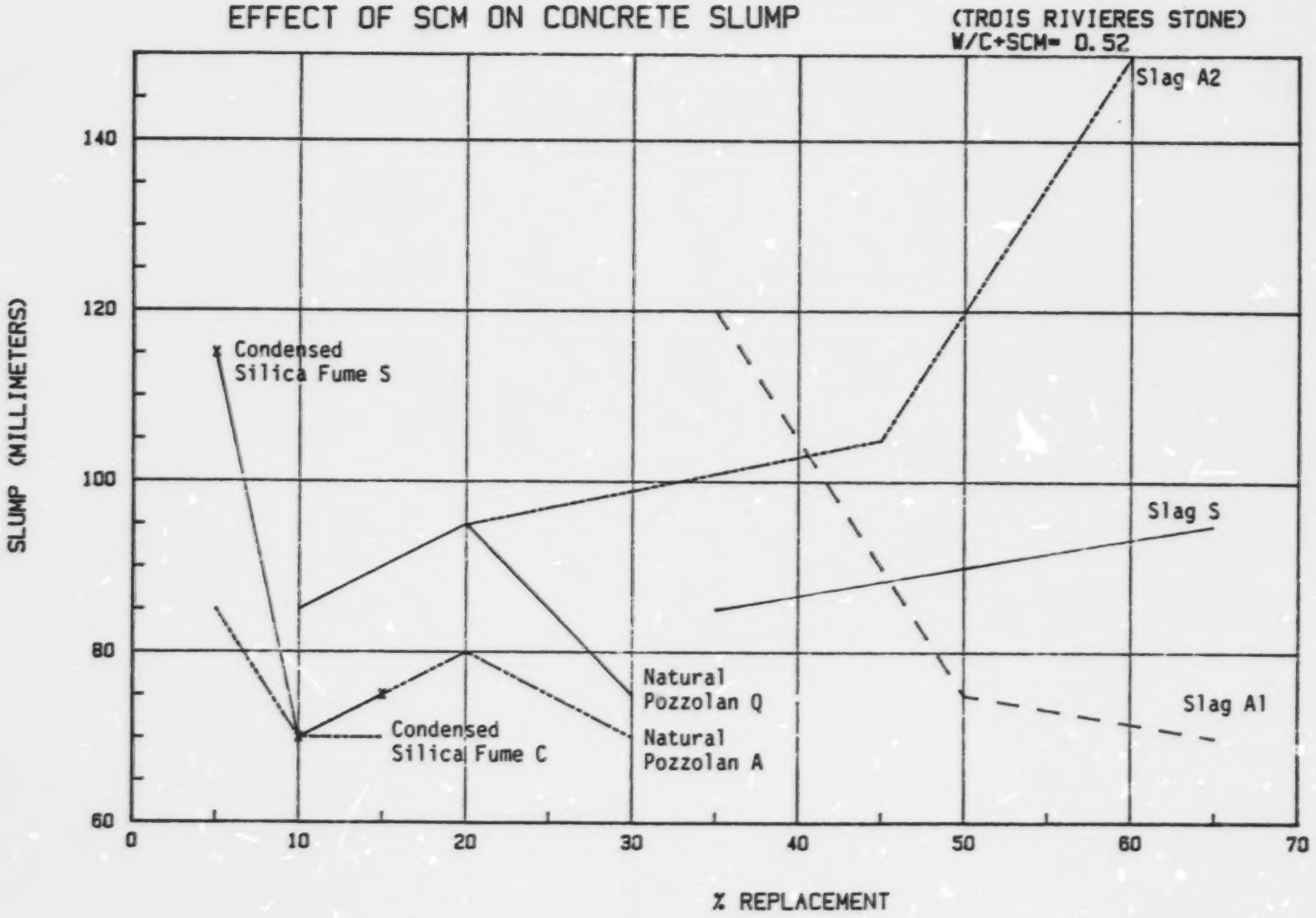

EFFECT OF SCM ON CONCRETE SLUMP
(TROIS RIVIERES STONE)
W/C+SCM= 0.52
SLUMP (MILLIMETERS)
140
120
100
80
60
0
10
20
30
40
50
60
70
% REPLACEMENT
Slag A2
Slag S
Slag A1
Condensed
Silica Fume S
Condensed
Silica Fume C
Natural
Pozzolan Q
Natural
Pozzolan A

Figure 24

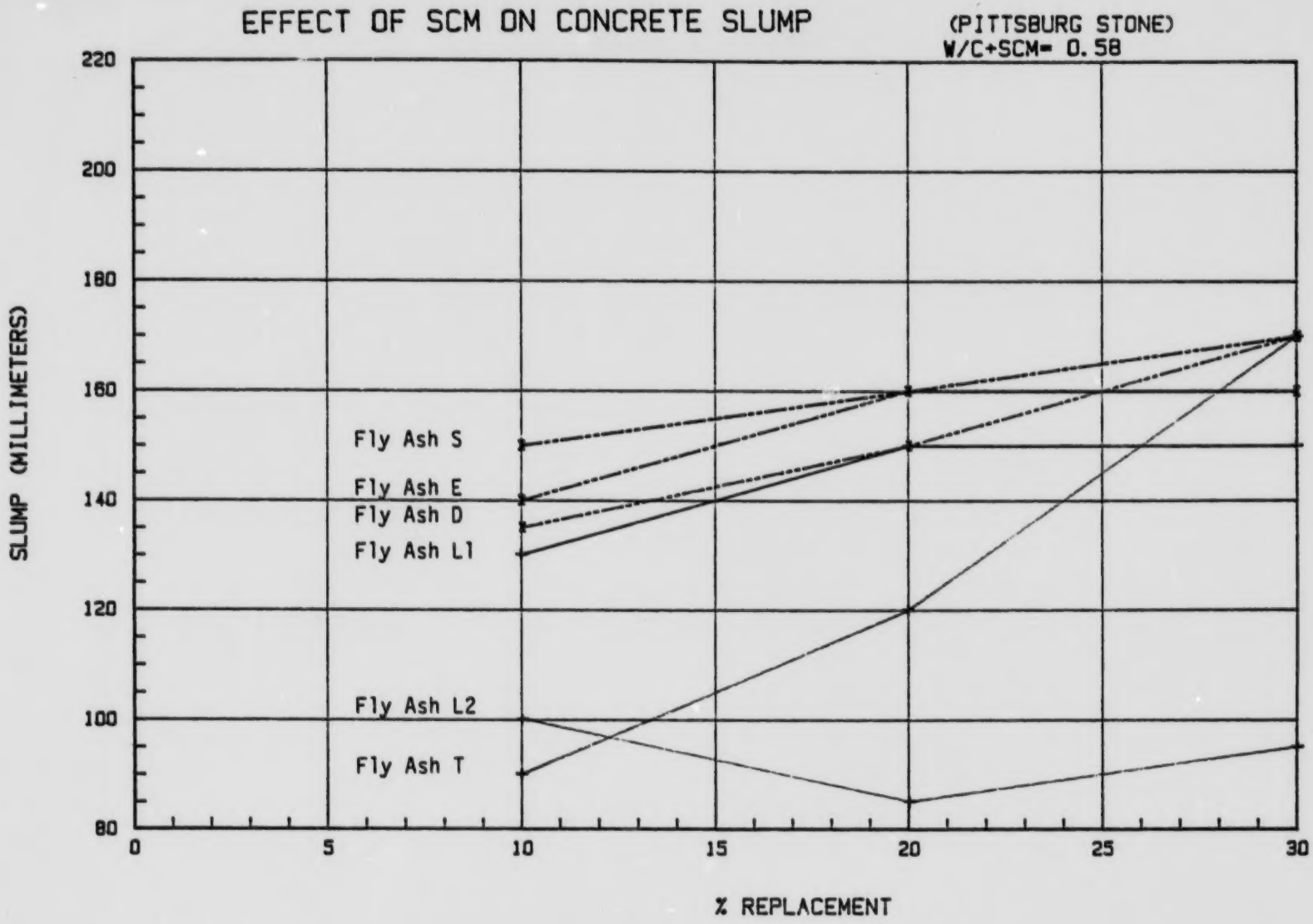

EFFECT OF SCM ON CONCRETE SLUMP
(PITTSBURG STONE)
W/C+SCM= 0.58
SLUMP (MILLIMETERS)
220
200
180
160
140
120
100
80
0
5
10
15
20
25
30
% REPLACEMENT
Fly Ash S
Fly Ash E
Fly Ash D
Fly Ash L1
Fly Ash L2
Fly Ash T

Figure 25

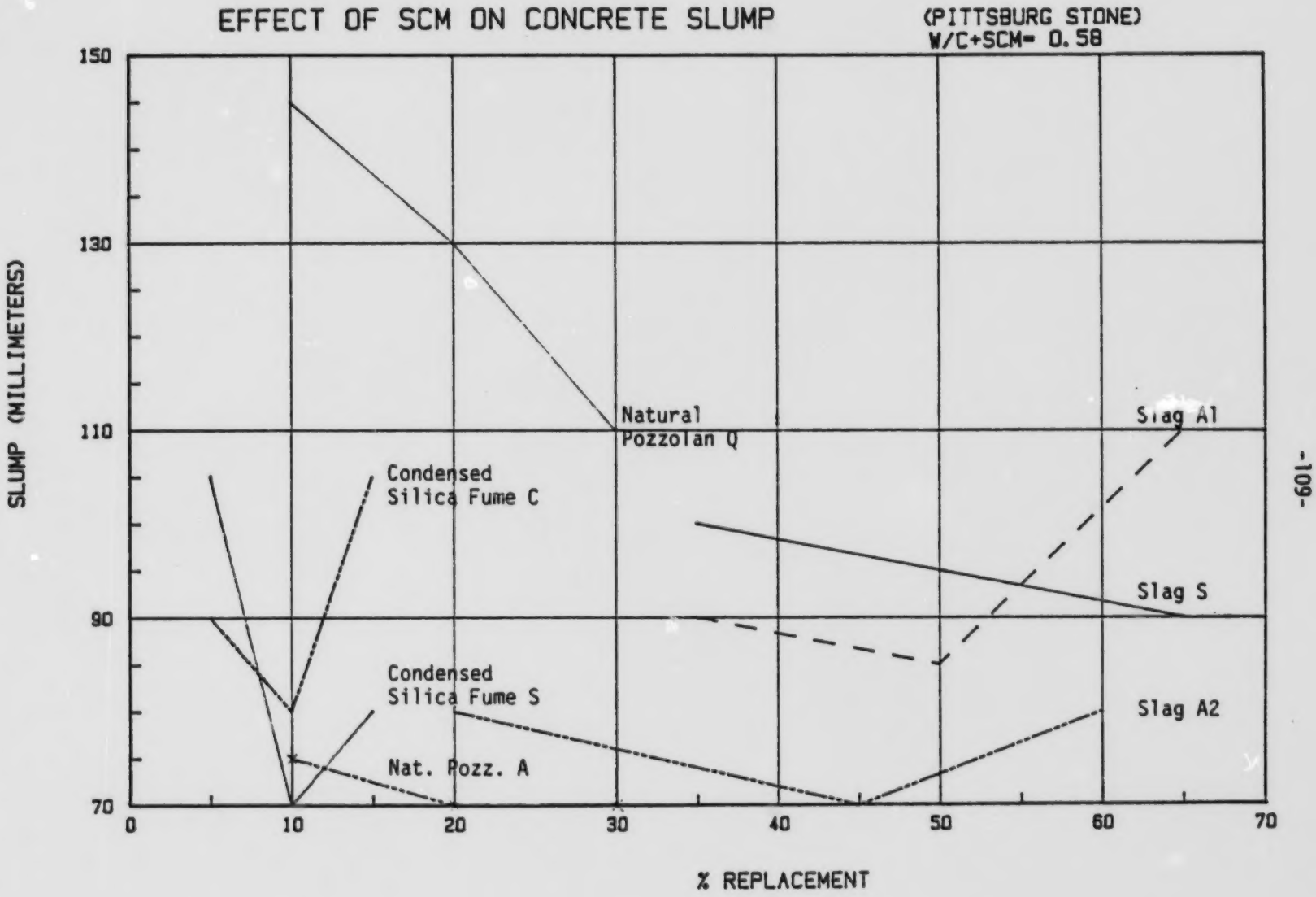

EFFECT OF SCM ON CONCRETE SLUMP
(PITTSBURG STONE)
W/C+SCM= 0.58
SLUMP (MILLIMETERS)
150
130
110
90
70
0
10
20
30
40
50
60
70
% REPLACEMENT
Natural
Pozzolan Q
Condensed
Silica Fume C
Condensed
Silica Fume S
Nat. Pozz. A
Slag A1
Slag S
Slag A2

Figure 26

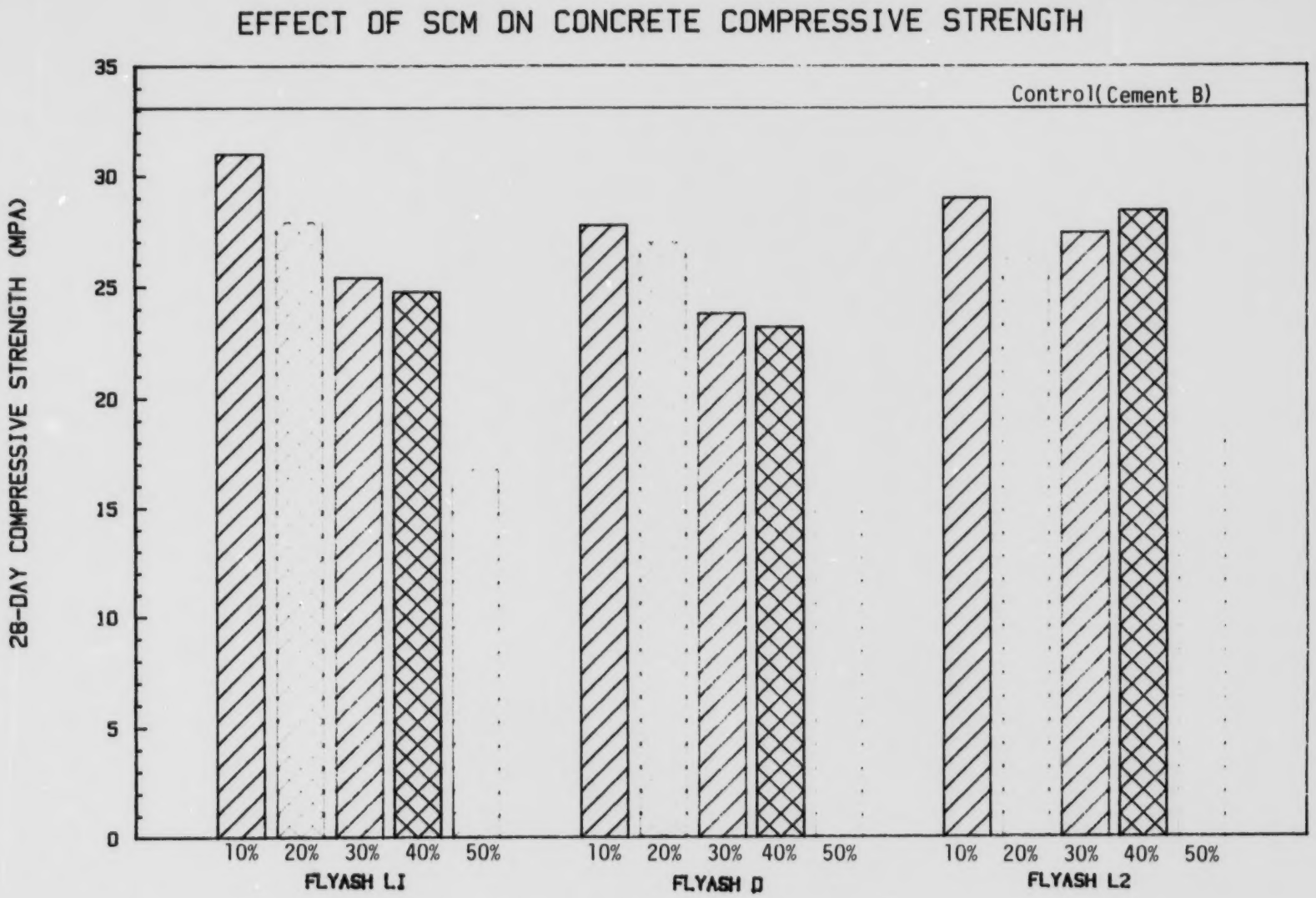

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
35
30
25
20
15
10
5
0
Control(Cement B)
10%
20%
30%
40%
50%
FLYASH L1
FLYASH D
FLYASH L2

Figure 27

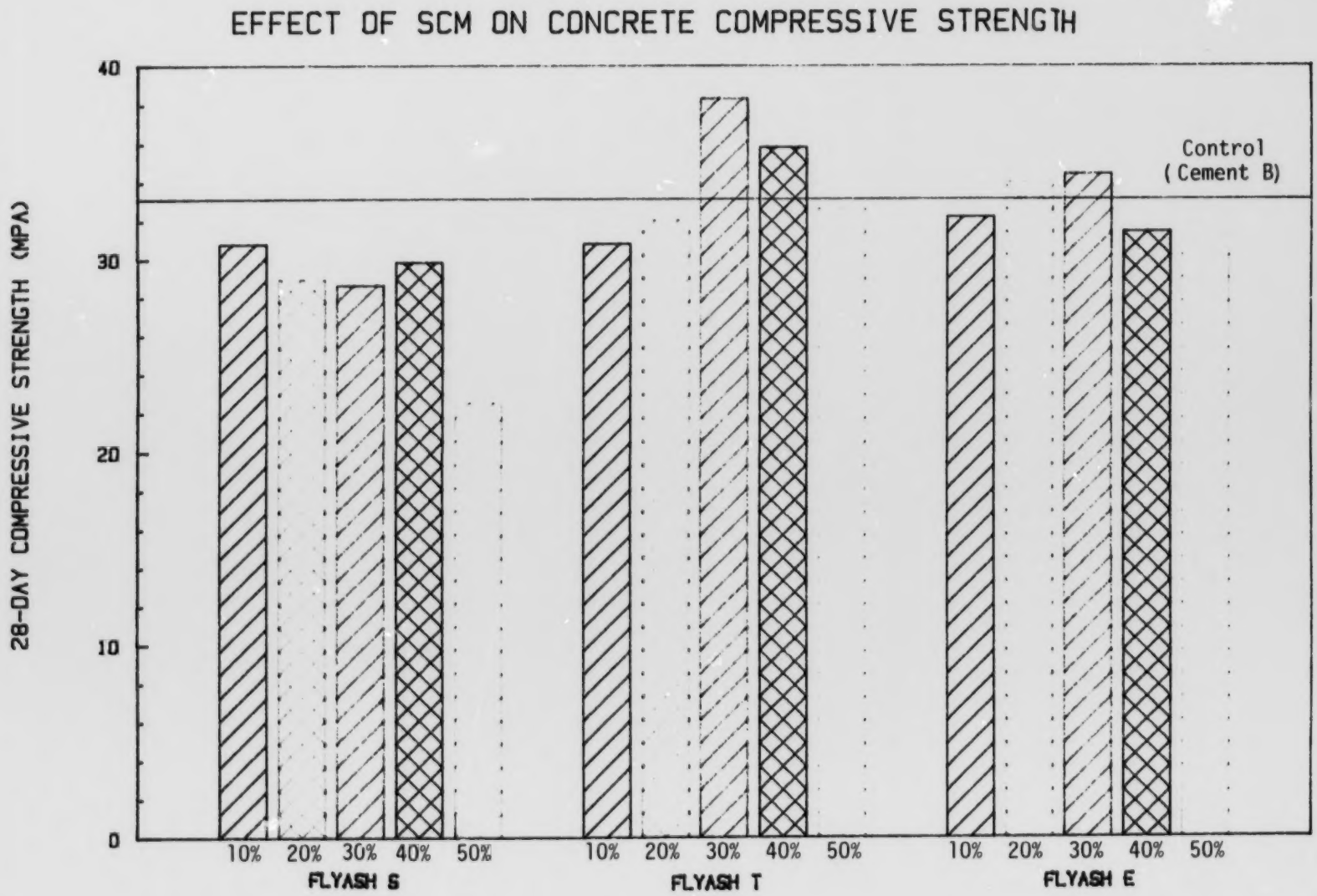

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
40
30
20
10
0
Control
(Cement B)
10%
20%
30%
40%
50%
FLYASH S
FLYASH T
FLYASH E

Figure 28

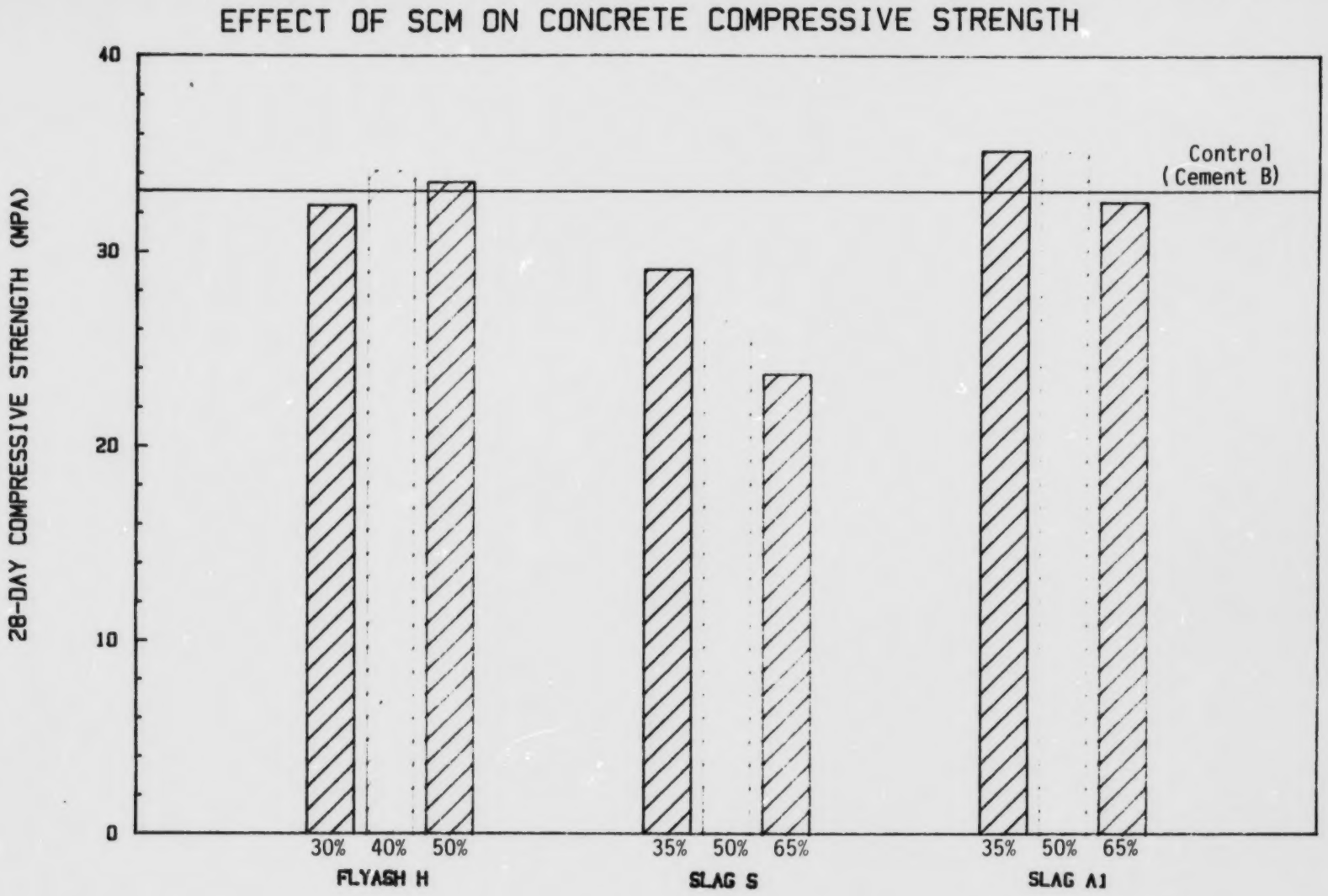

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
40
30
20
10
0
Control
(Cement B)
30%
40%
50%
FLYASH H
35%
50%
65%
SLAG S
35%
50%
65%
SLAG A1

Figure 29

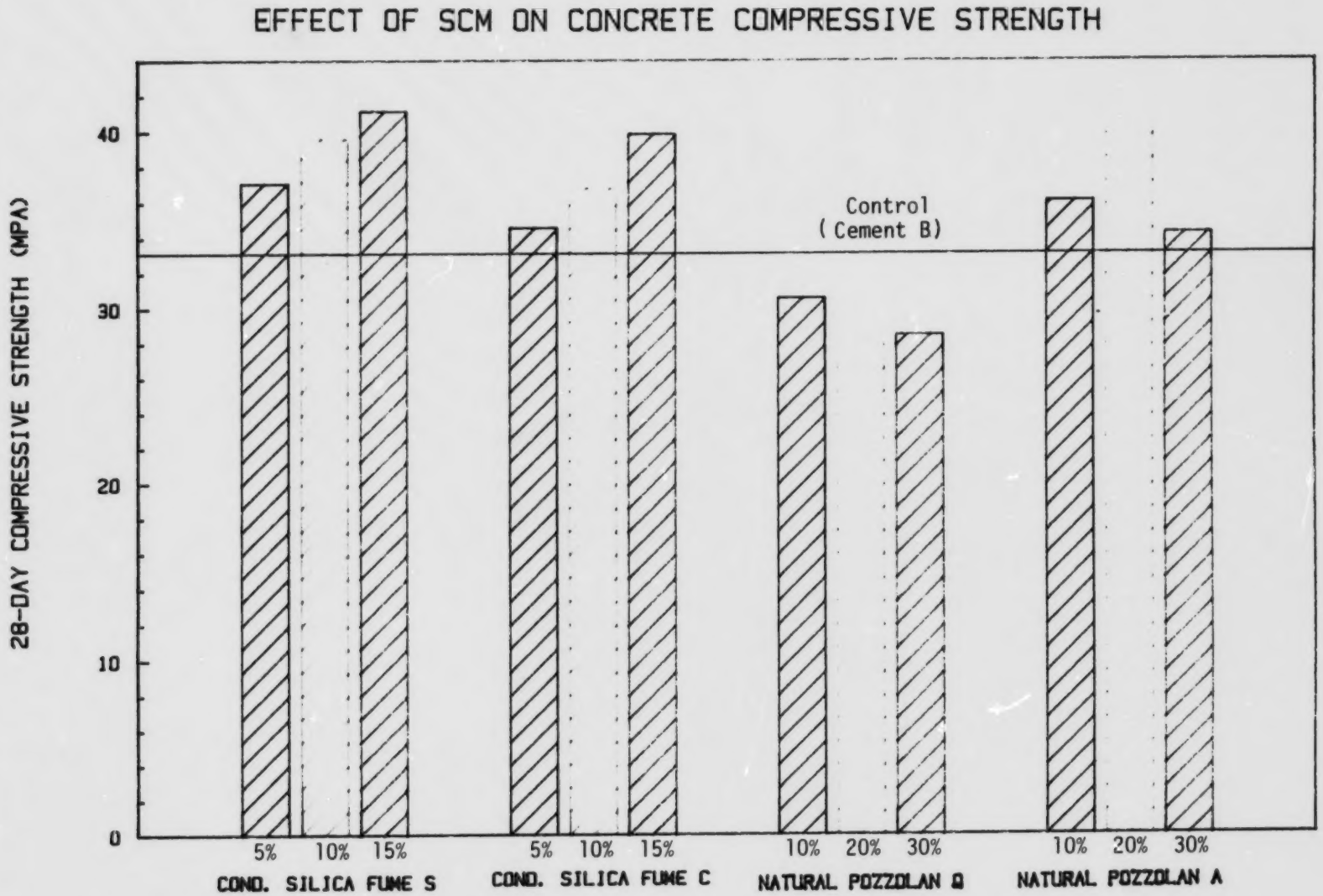

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
0
10
20
30
40
Control
(Cement B)
5%
10%
15%
COND. SILICA FUME S
5%
10%
15%
COND. SILICA FUME C
10%
20%
30%
NATURAL POZZOLAN Q
10%
20%
30%
NATURAL POZZOLAN A

Figure 30

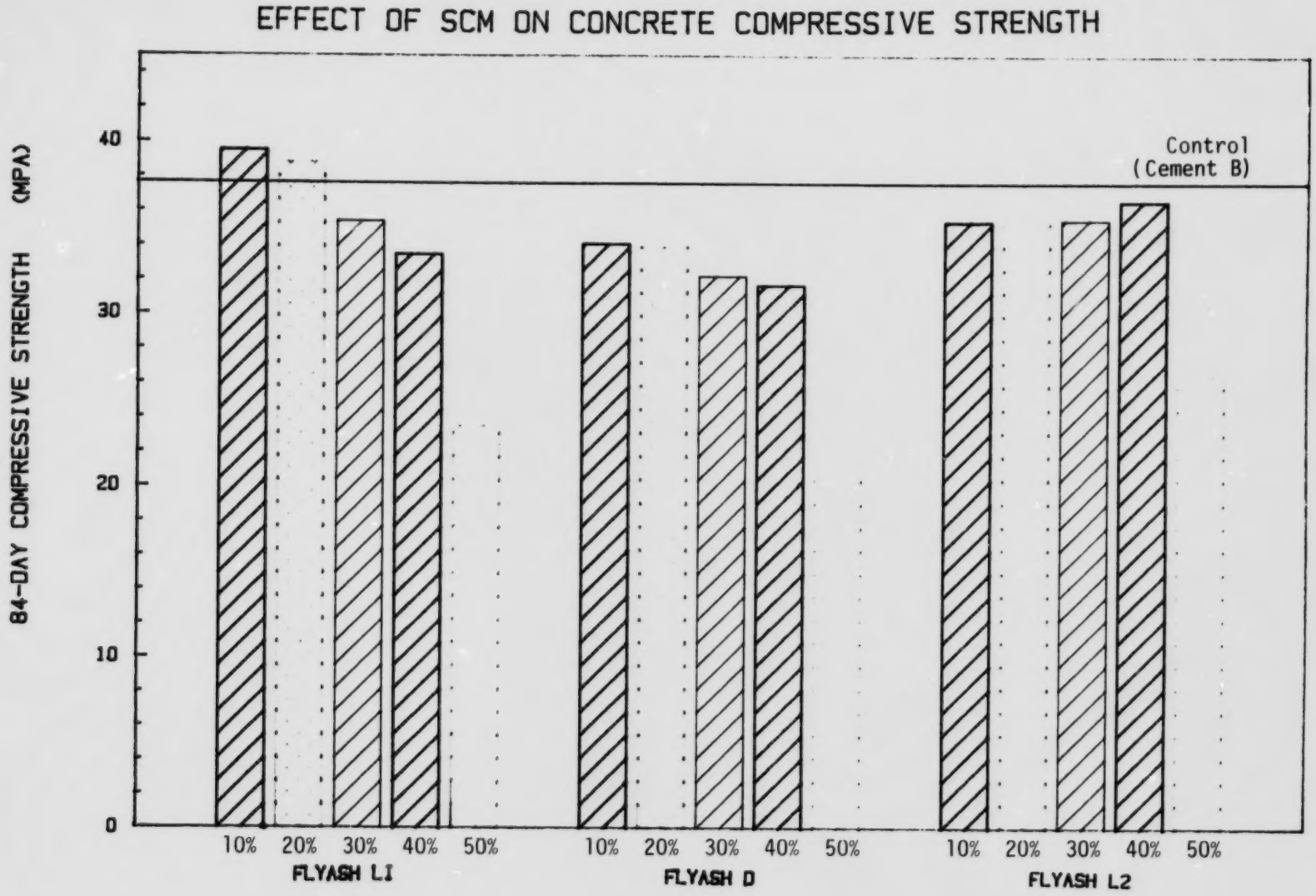

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
84-DAY COMPRESSIVE STRENGTH (MPA)
0
10
20
30
40
Control
(Cement B)
10% 20% 30% 40% 50%
FLYASH L1
10% 20% 30% 40% 50%
FLYASH D
10% 20% 30% 40% 50%
FLYASH L2

Figure 31

(Lady Evelyn Lake Stone)

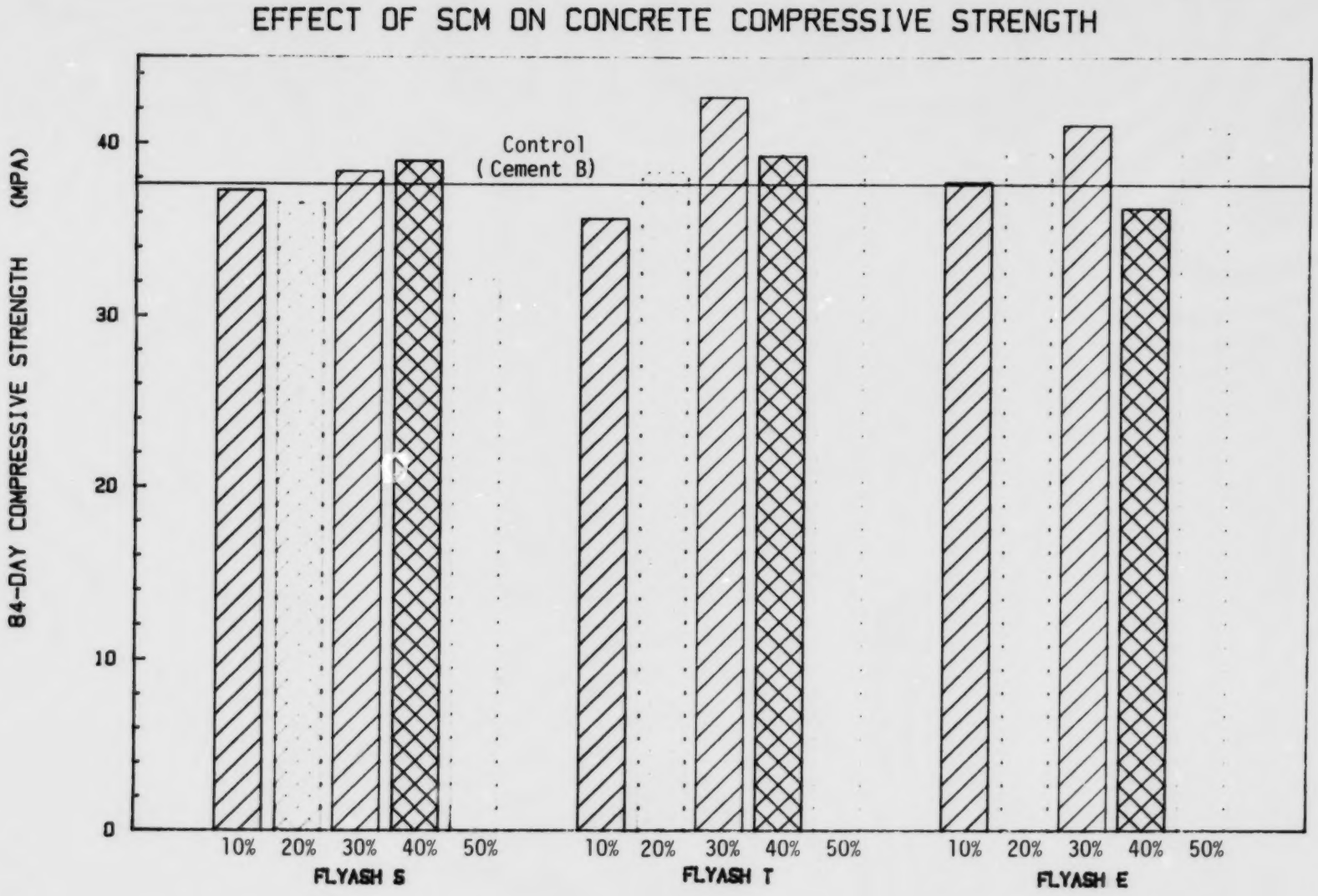


Figure 32

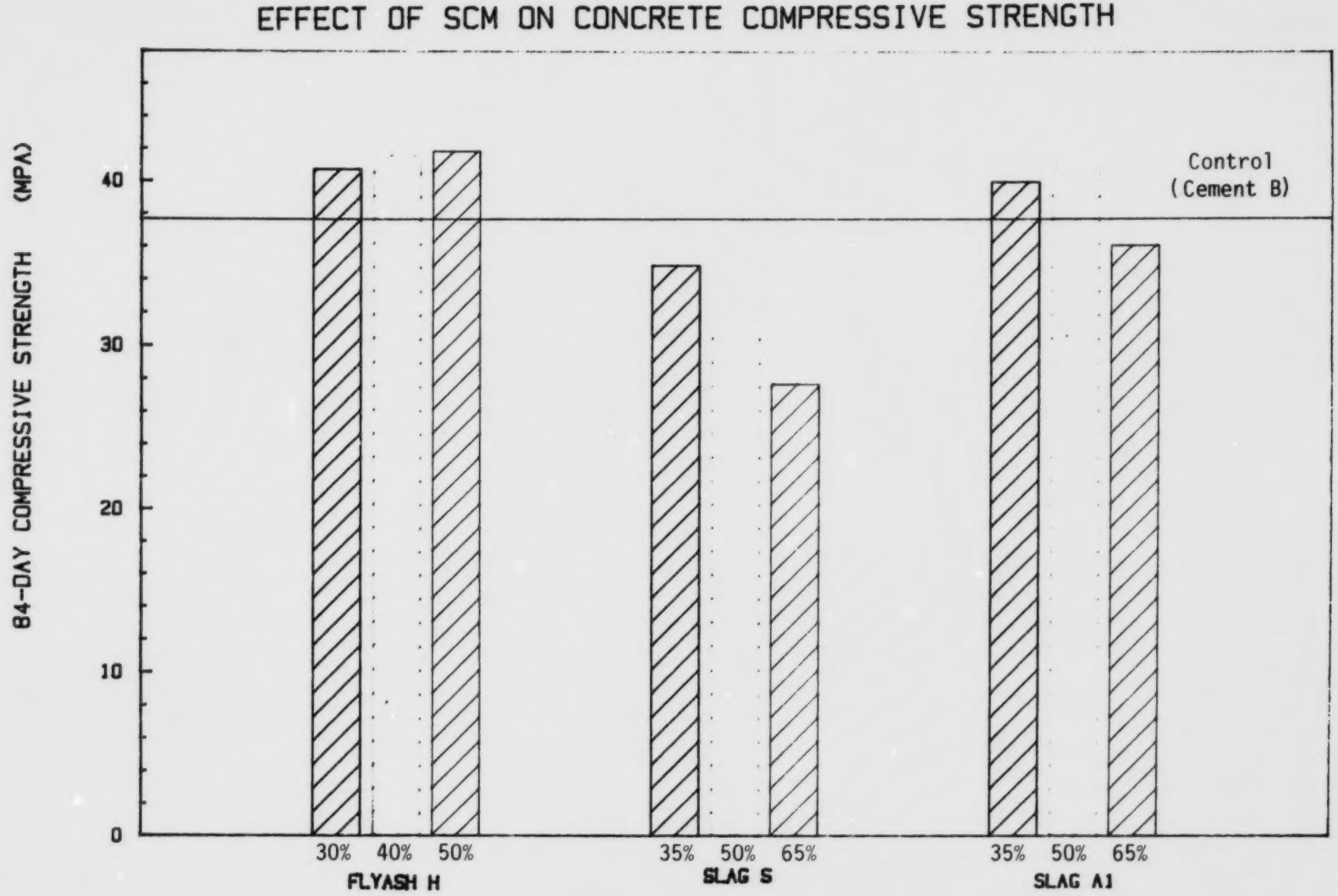

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
84-DAY COMPRESSIVE STRENGTH (MPA)
0
10
20
30
40
Control
(Cement B)
30%
40%
50%
FLYASH H
35%
50%
65%
SLAG S
35%
50%
65%
SLAG A1

Figure 33

(Lady Evelyn Lake Stone)

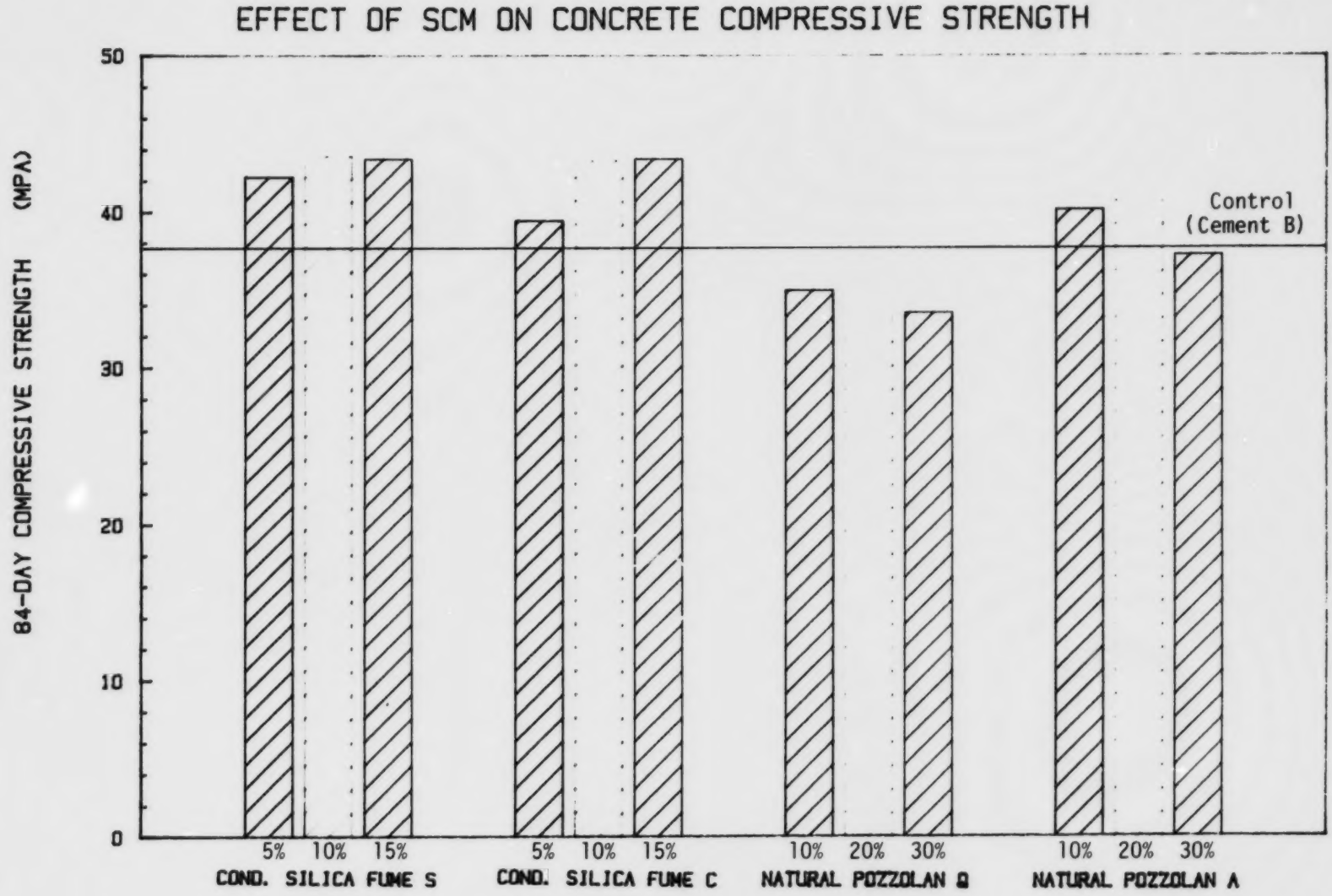


Figure 34

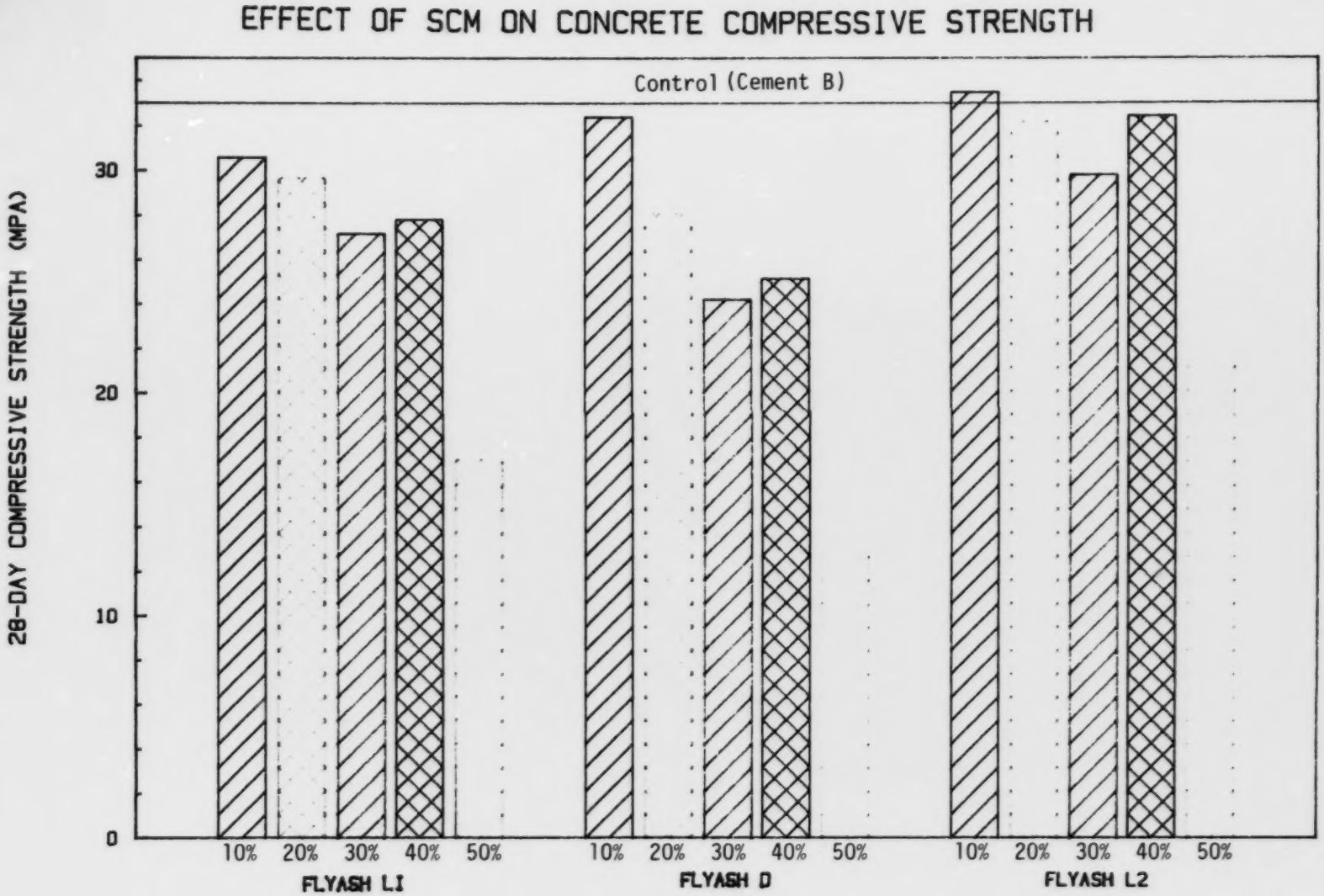

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
Control (Cement B)
28-DAY COMPRESSIVE STRENGTH (MPA)
0
10
20
30
10%
20%
30%
40%
50%
FLYASH LI
FLYASH D
FLYASH L2

Figure 35

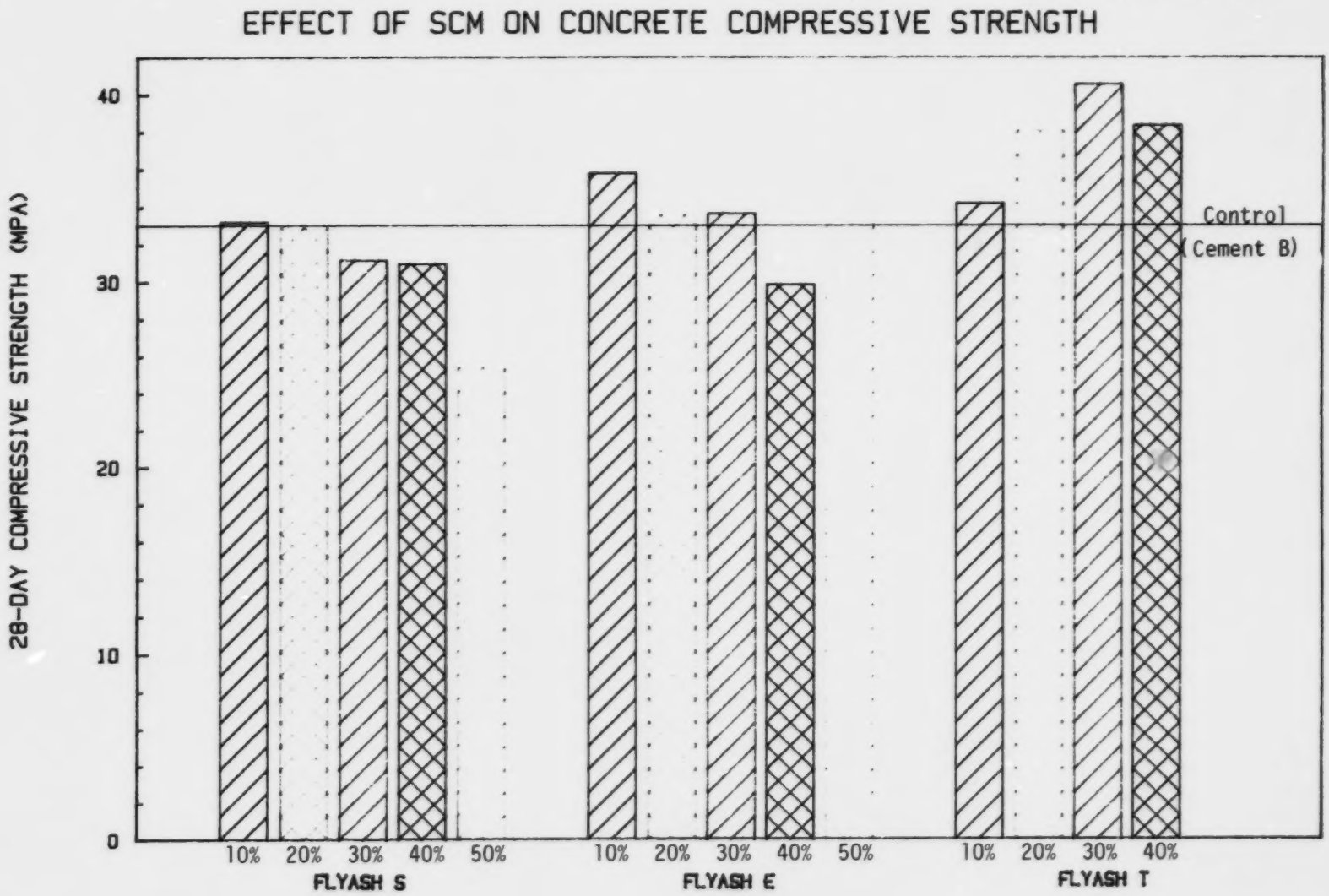

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
40
30
20
10
0
Control
(Cement B)
10%
20%
30%
40%
50%
FLYASH S
FLYASH E
FLYASH T

Figure 36

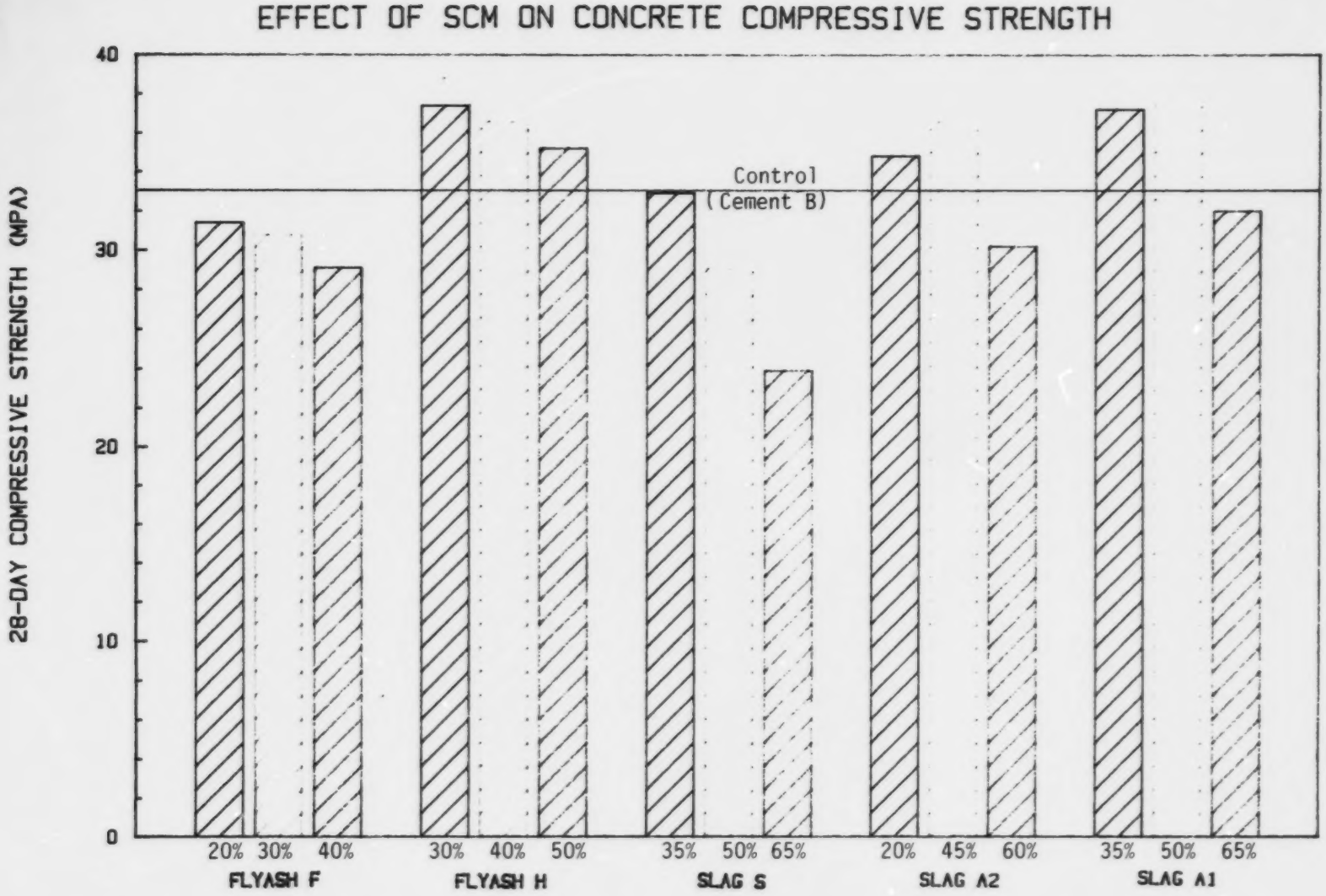

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
28-DAY COMPRESSIVE STRENGTH (MPA)
40
30
20
10
0
Control
(Cement B)
20% 30% 40%
30% 40% 50%
35% 50% 65%
20% 45% 60%
35% 50% 65%
FLYASH F
FLYASH H
SLAG S
SLAG A2
SLAG A1

Figure 37

(Trois Rivières Stone)

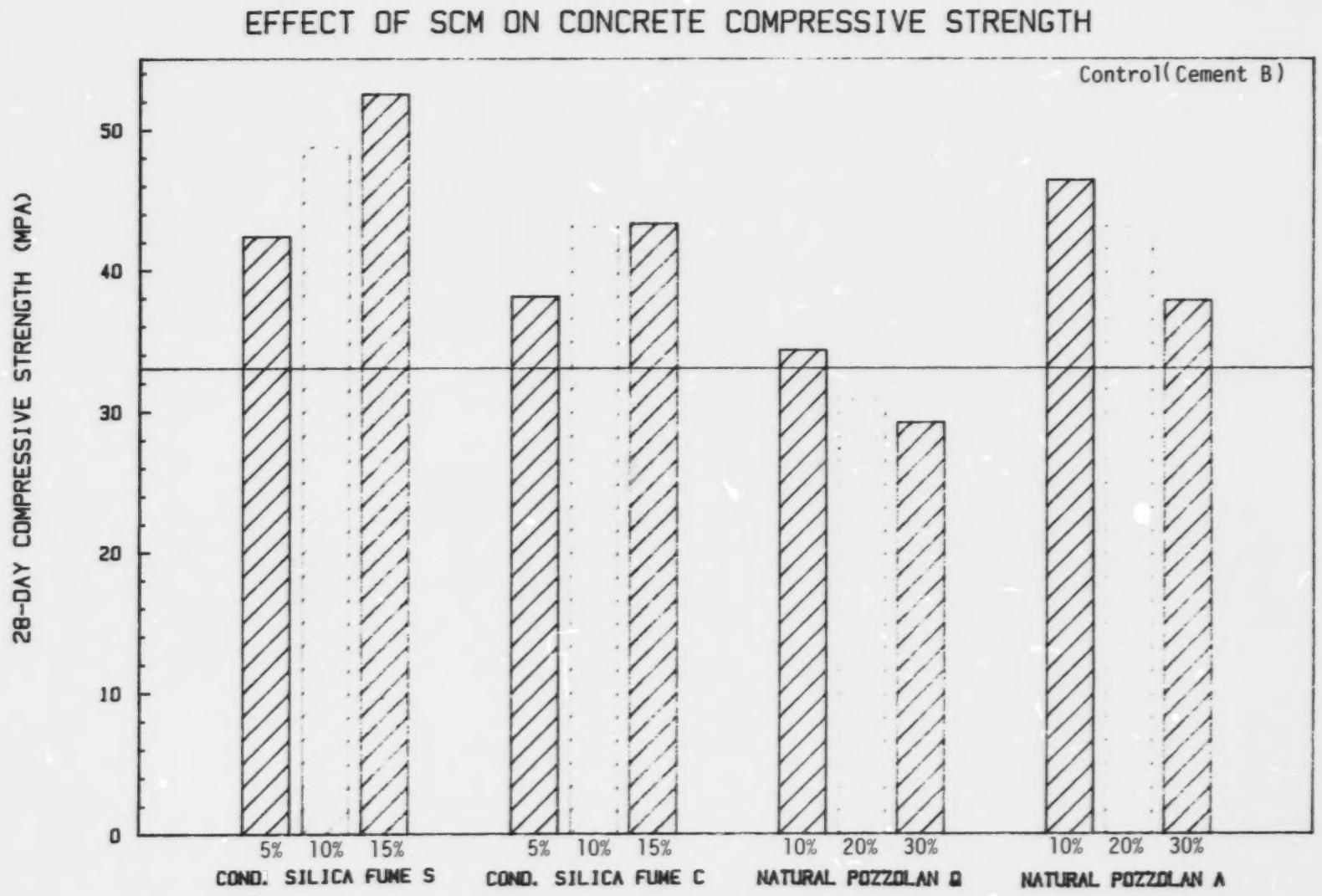


Figure 38

(Trois Rivières Stone)

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH

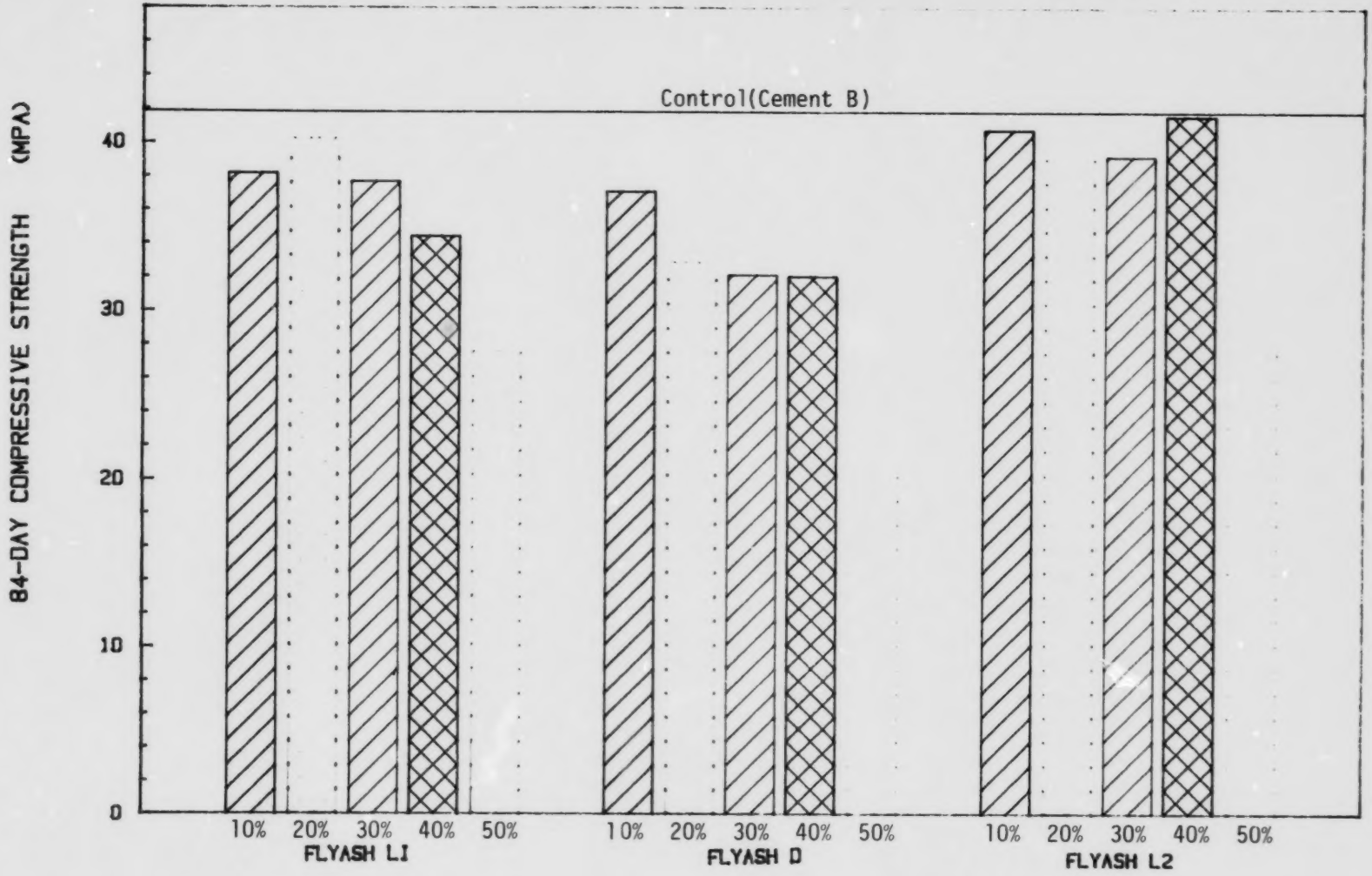


Figure 39

(Trois Rivières Stone)

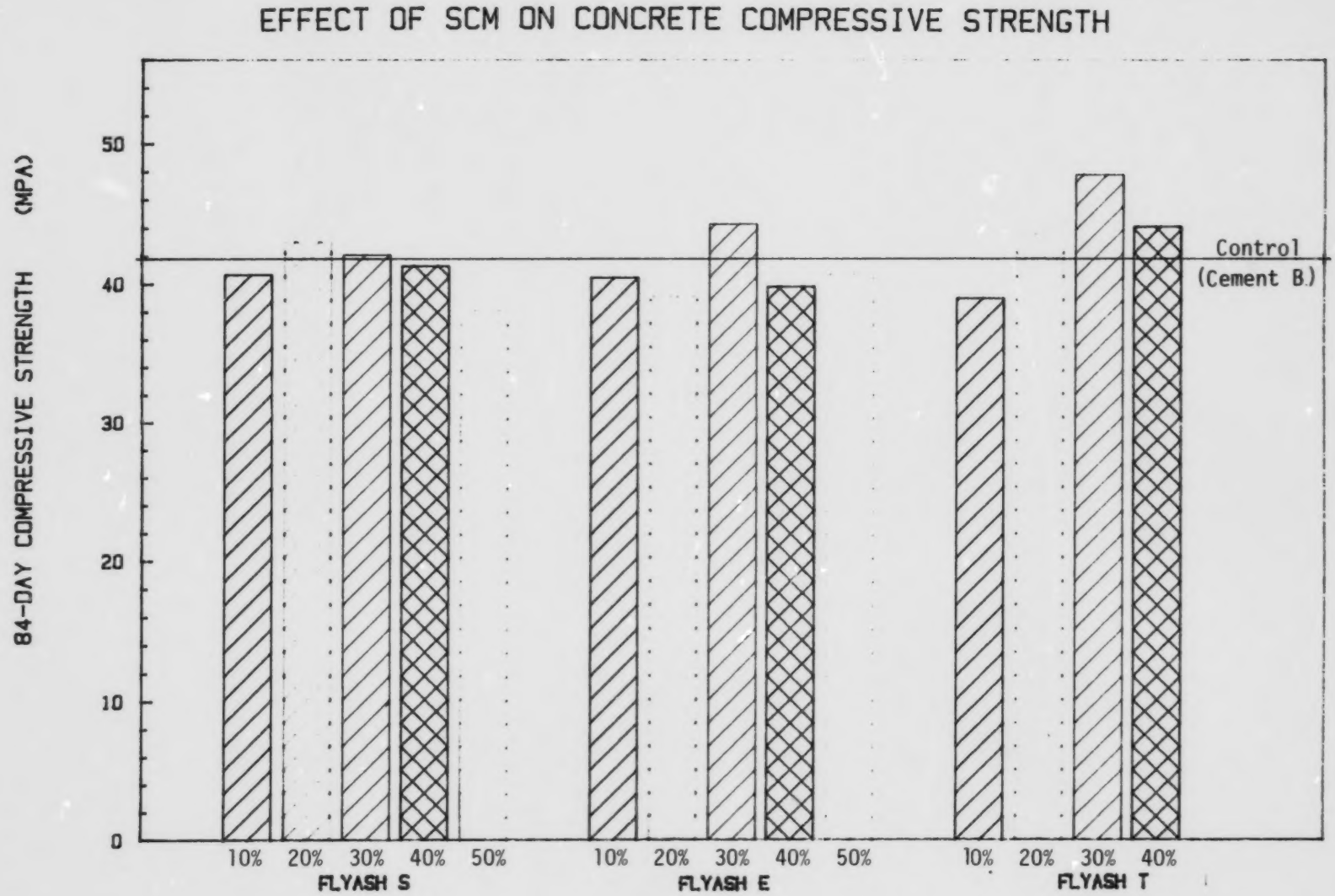


Figure 40

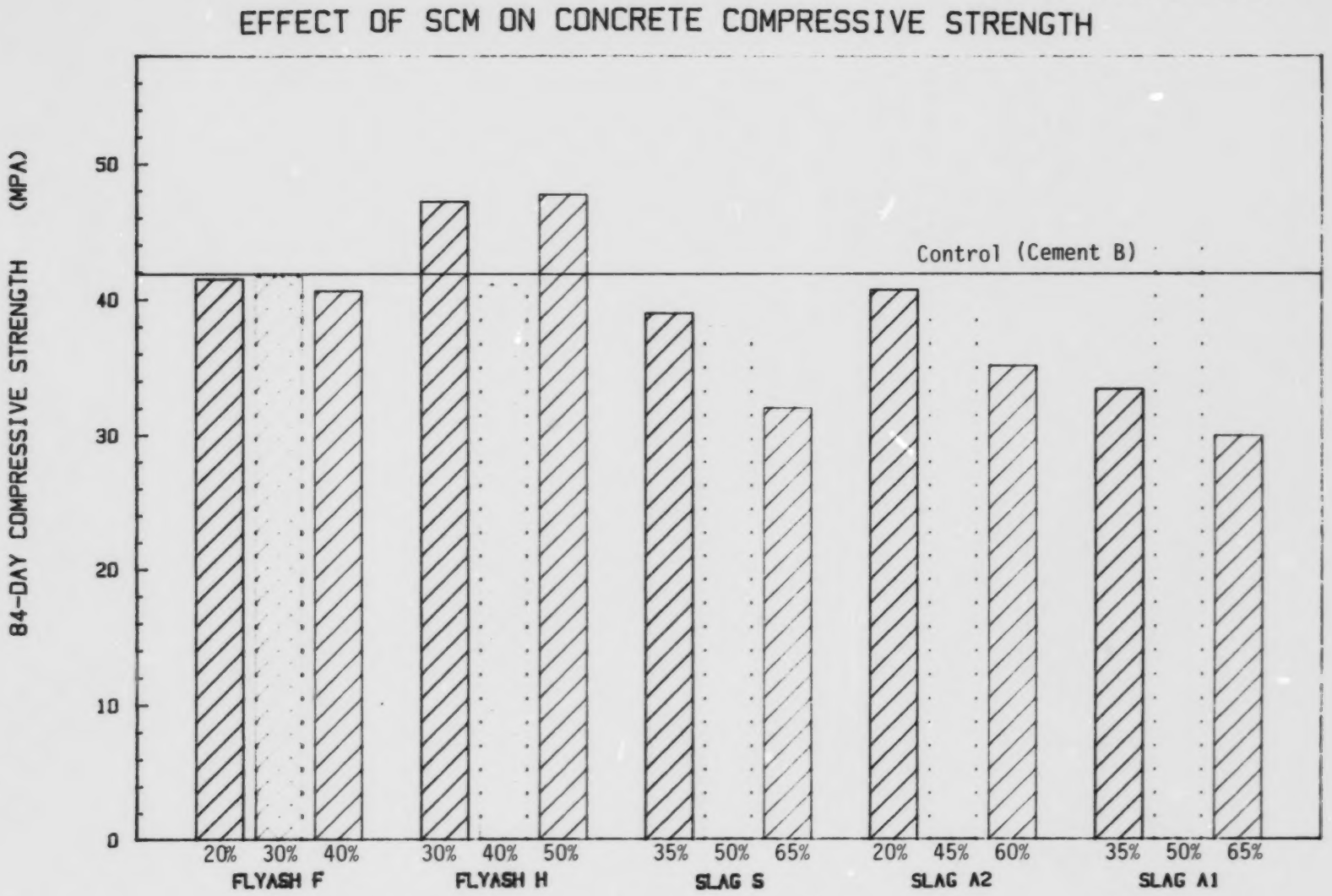

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
84-DAY COMPRESSIVE STRENGTH (MPA)
0
10
20
30
40
50
Control (Cement B)
20% 30% 40%
FLYASH F
30% 40% 50%
FLYASH H
35% 50% 65%
SLAG S
20% 45% 60%
SLAG A2
35% 50% 65%
SLAG A1

Figure 41

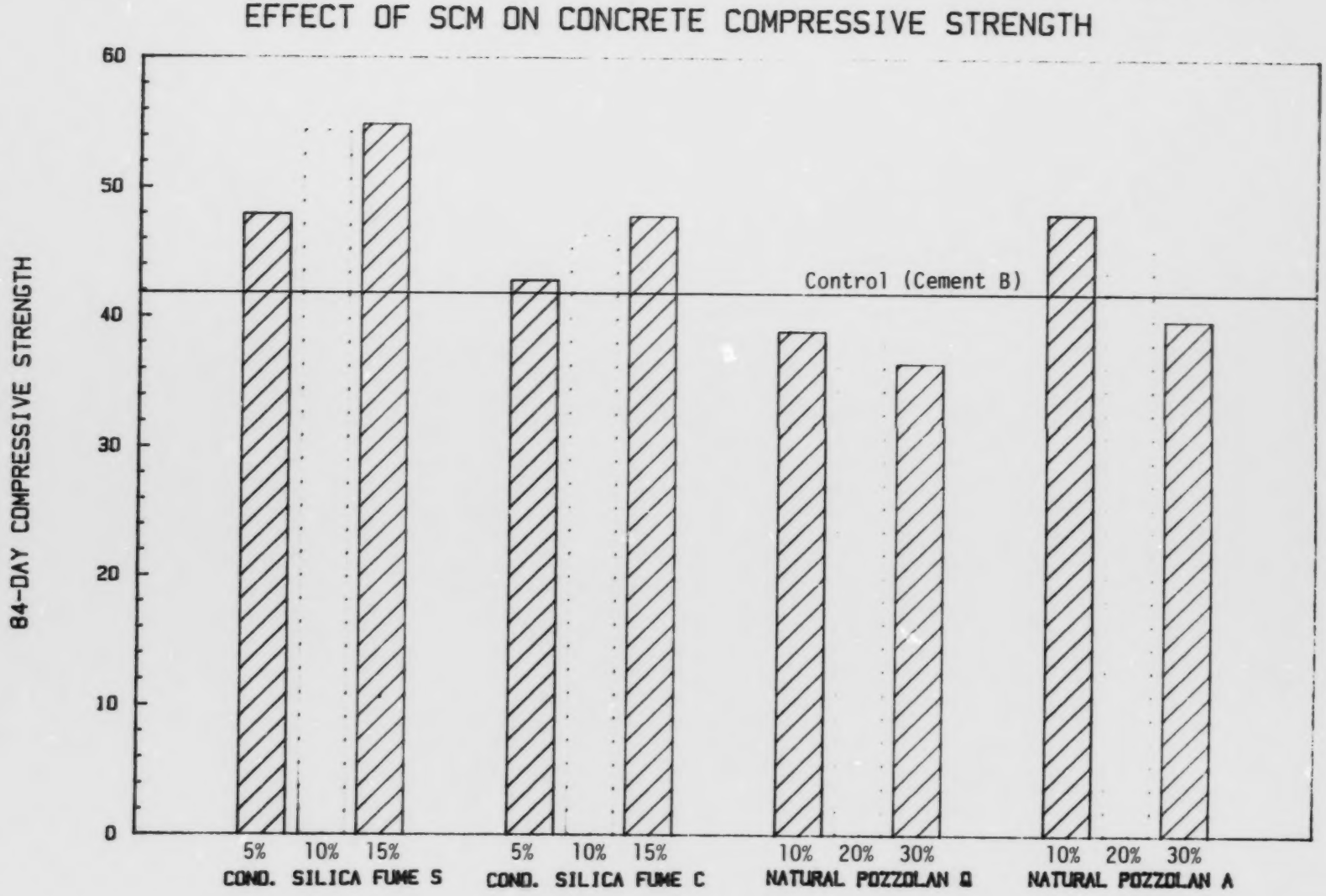

EFFECT OF SCM ON CONCRETE COMPRESSIVE STRENGTH
84-DAY COMPRESSIVE STRENGTH
60
50
40
30
20
10
0
Control (Cement B)
5% 10% 15%
COND. SILICA FUME S
5% 10% 15%
COND. SILICA FUME C
10% 20% 30%
NATURAL POZZOLAN Q
10% 20% 30%
NATURAL POZZOLAN A

Figure 42

(Pittsburgh Stone)

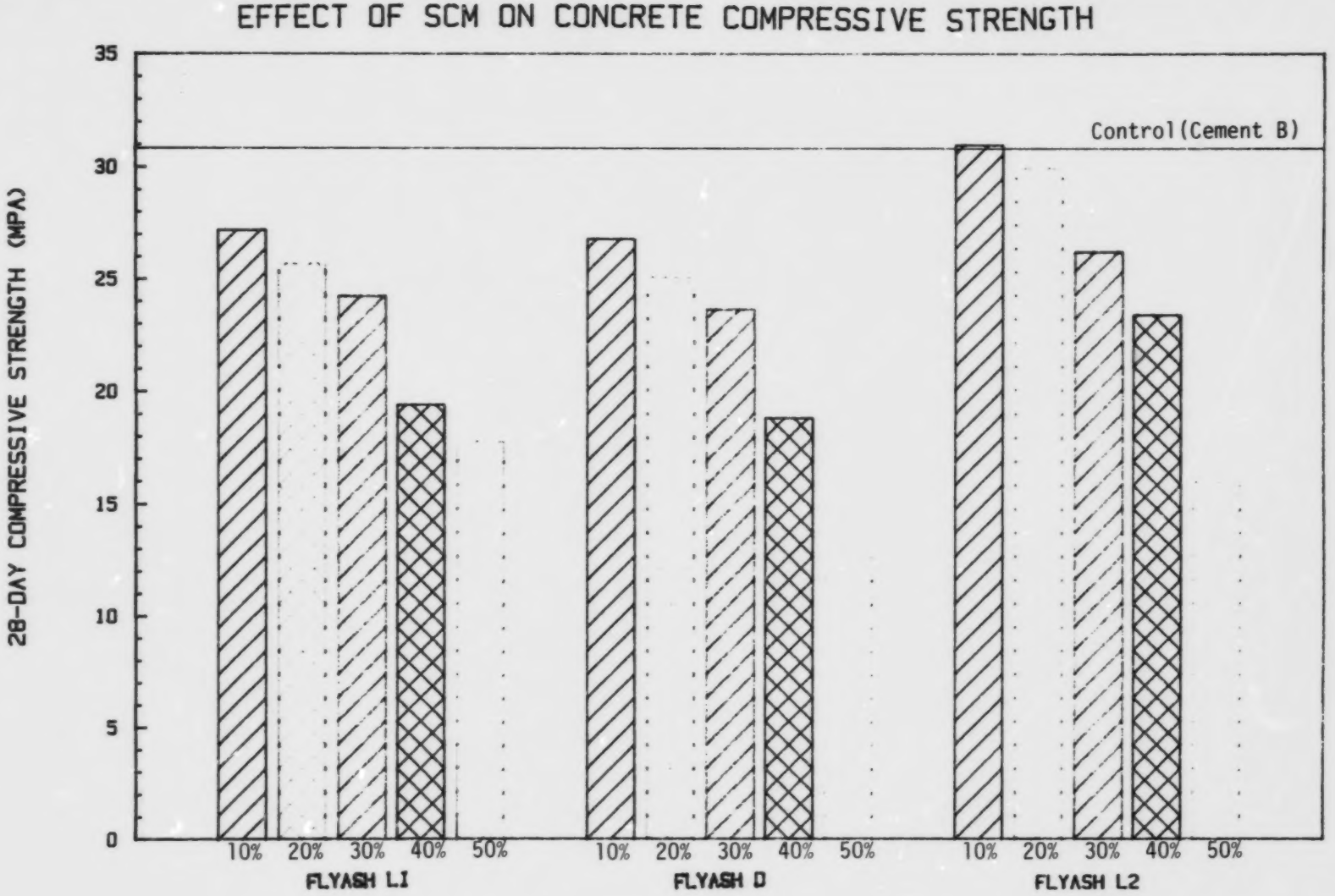


Figure 43

(Pittsburgh Stone)

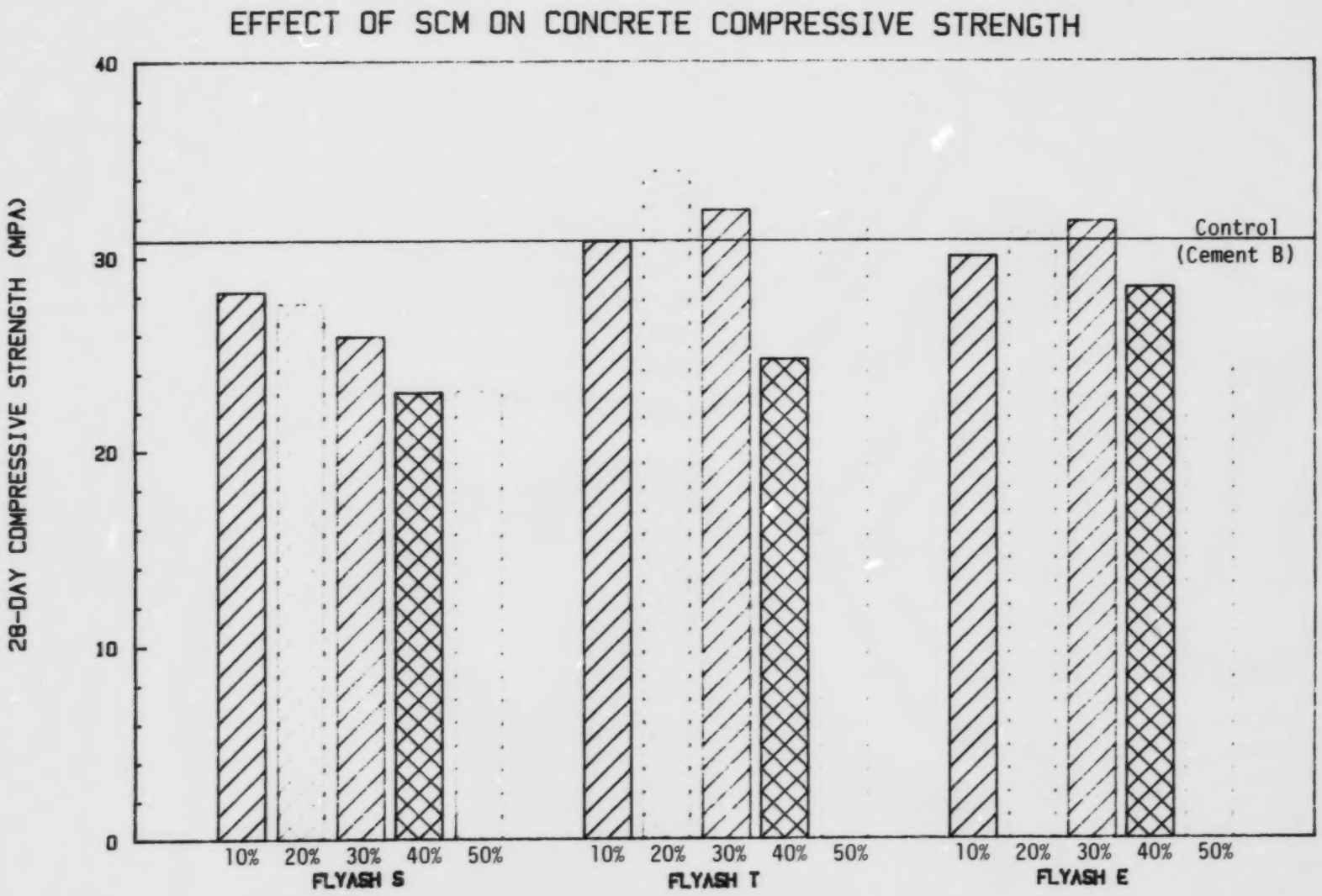


Figure 44

(Pittsburgh Stone)

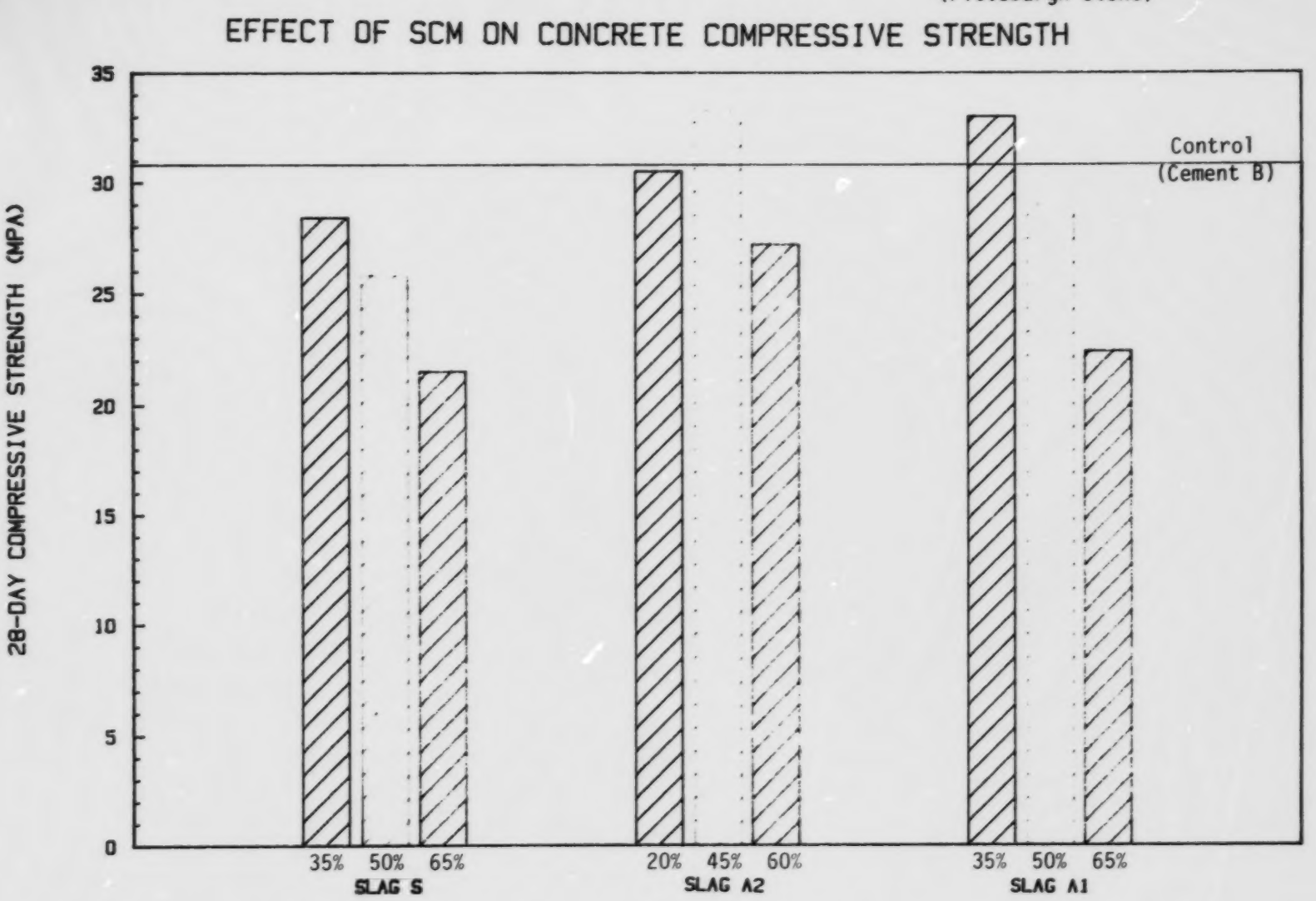


Figure 45

(Pittsburgh Stone)

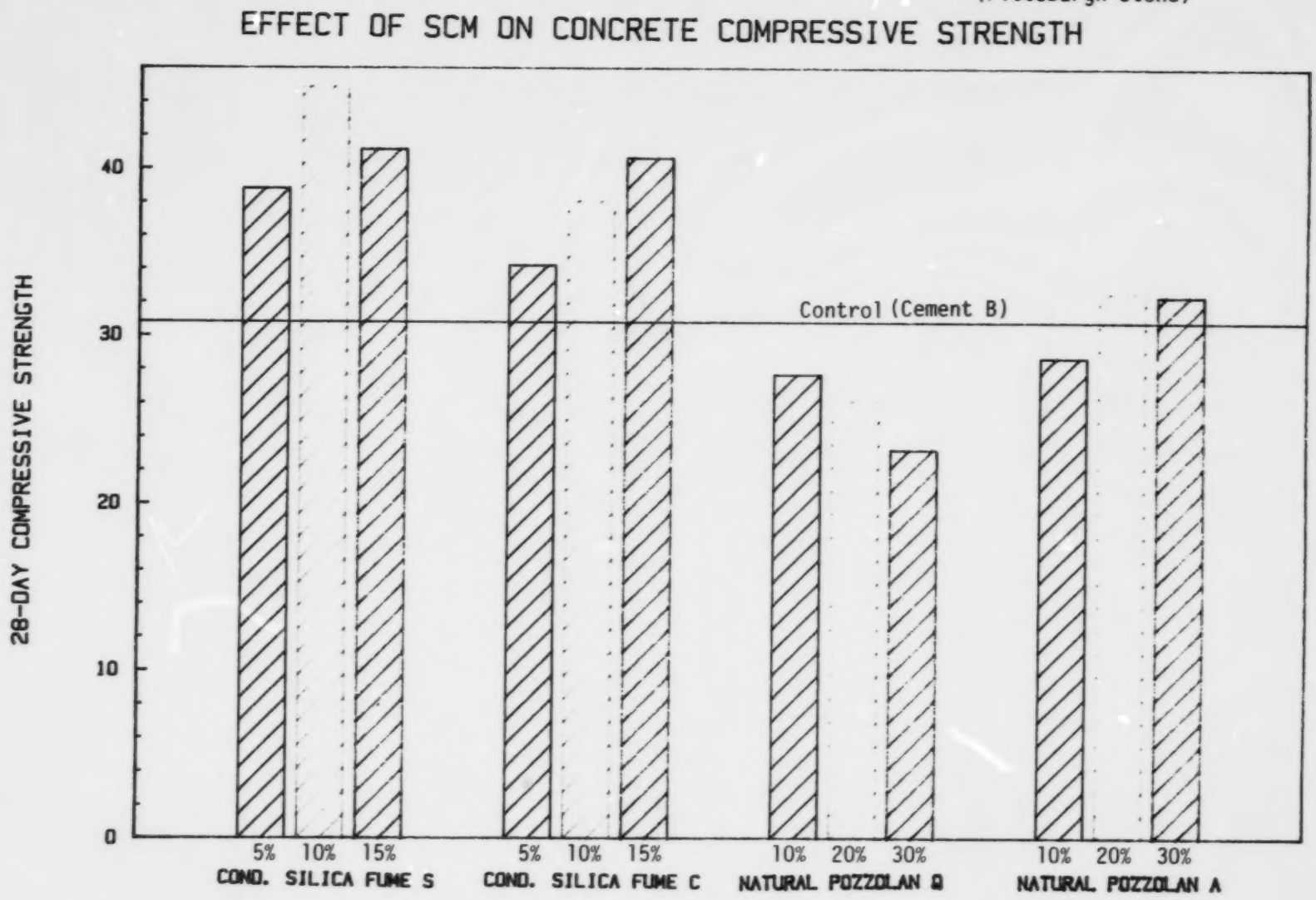


Figure 46

(Pittsburgh Stone)

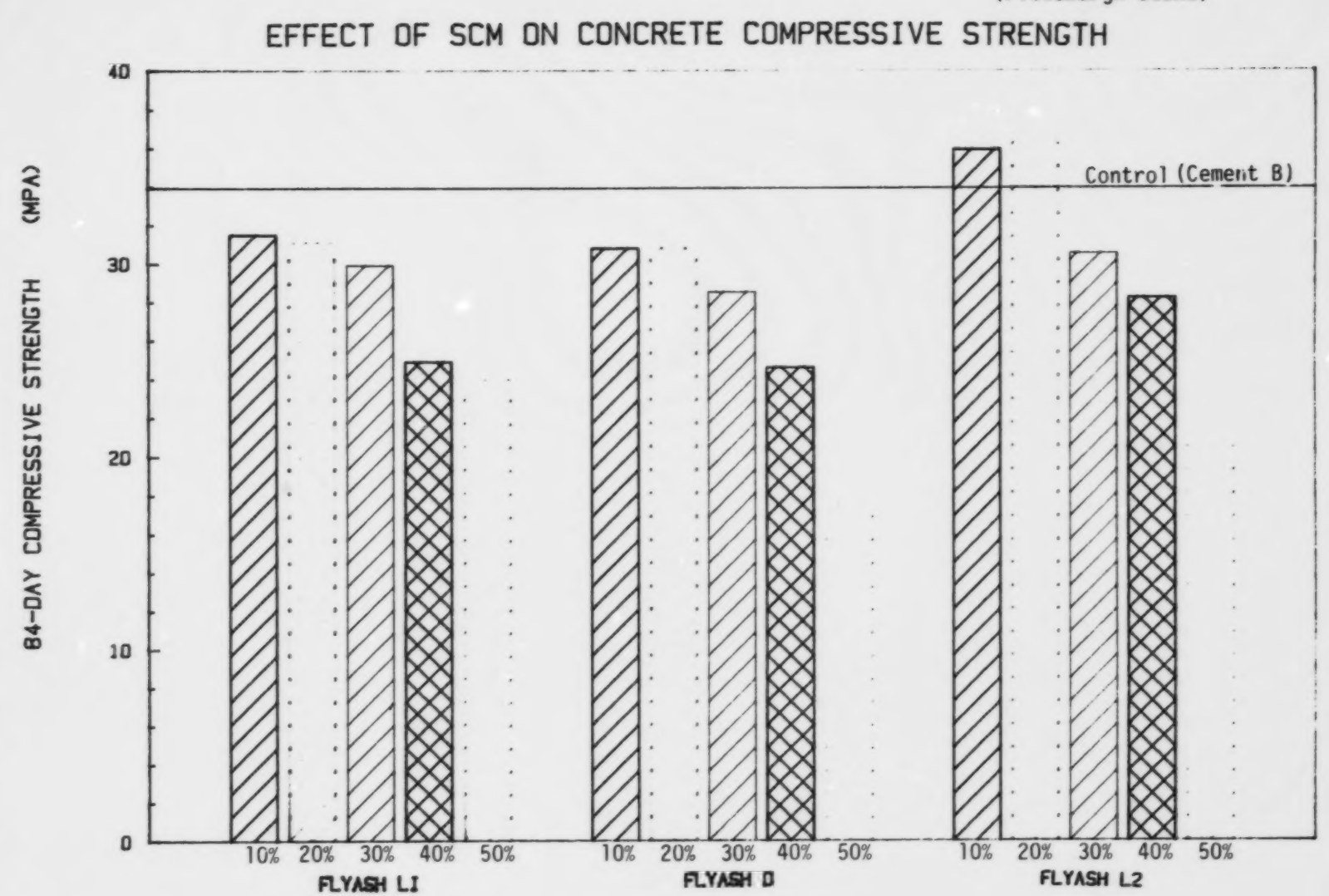


Figure 47

(Pittsburgh Stone)

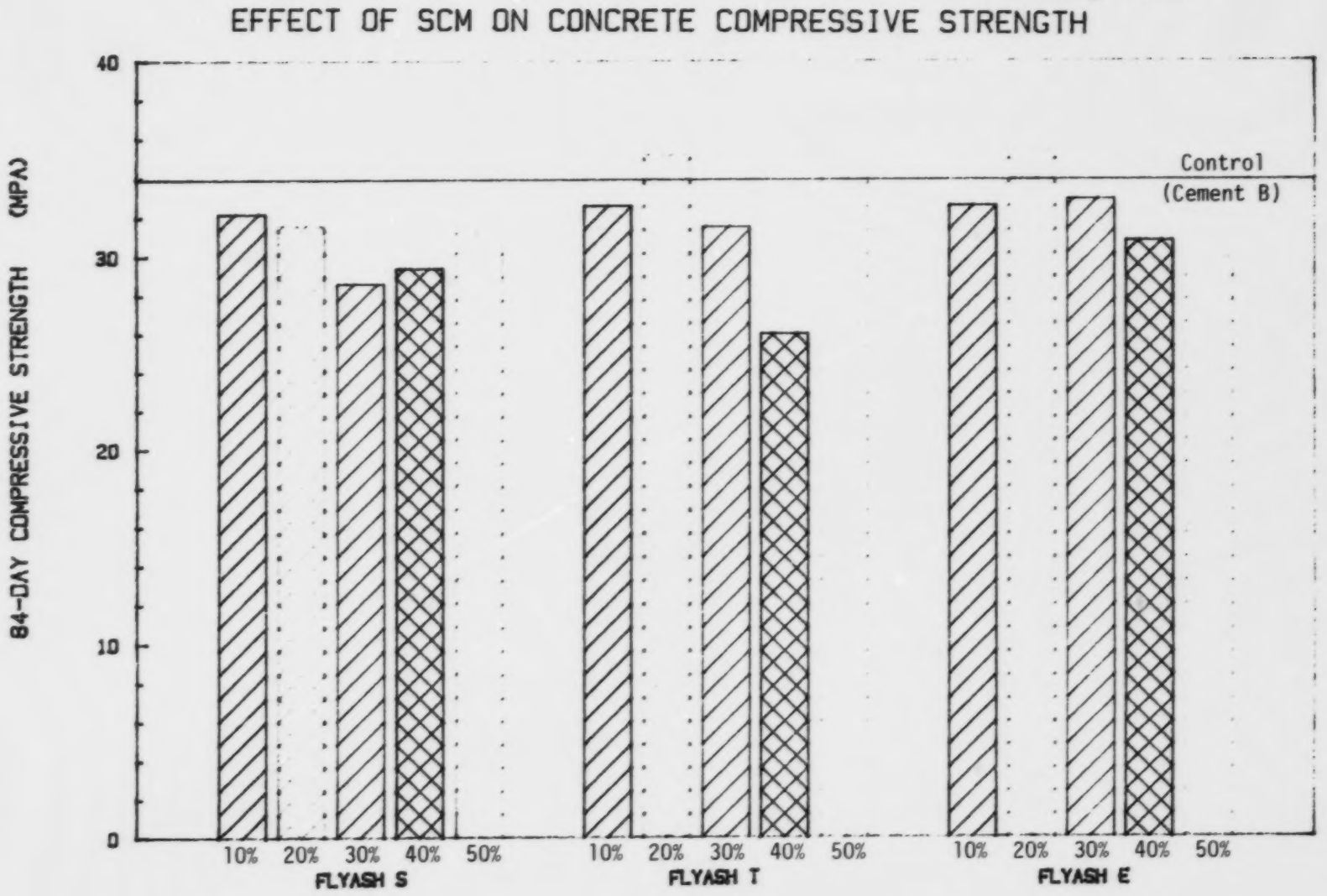


Figure 48

(Pittsburg Stone)

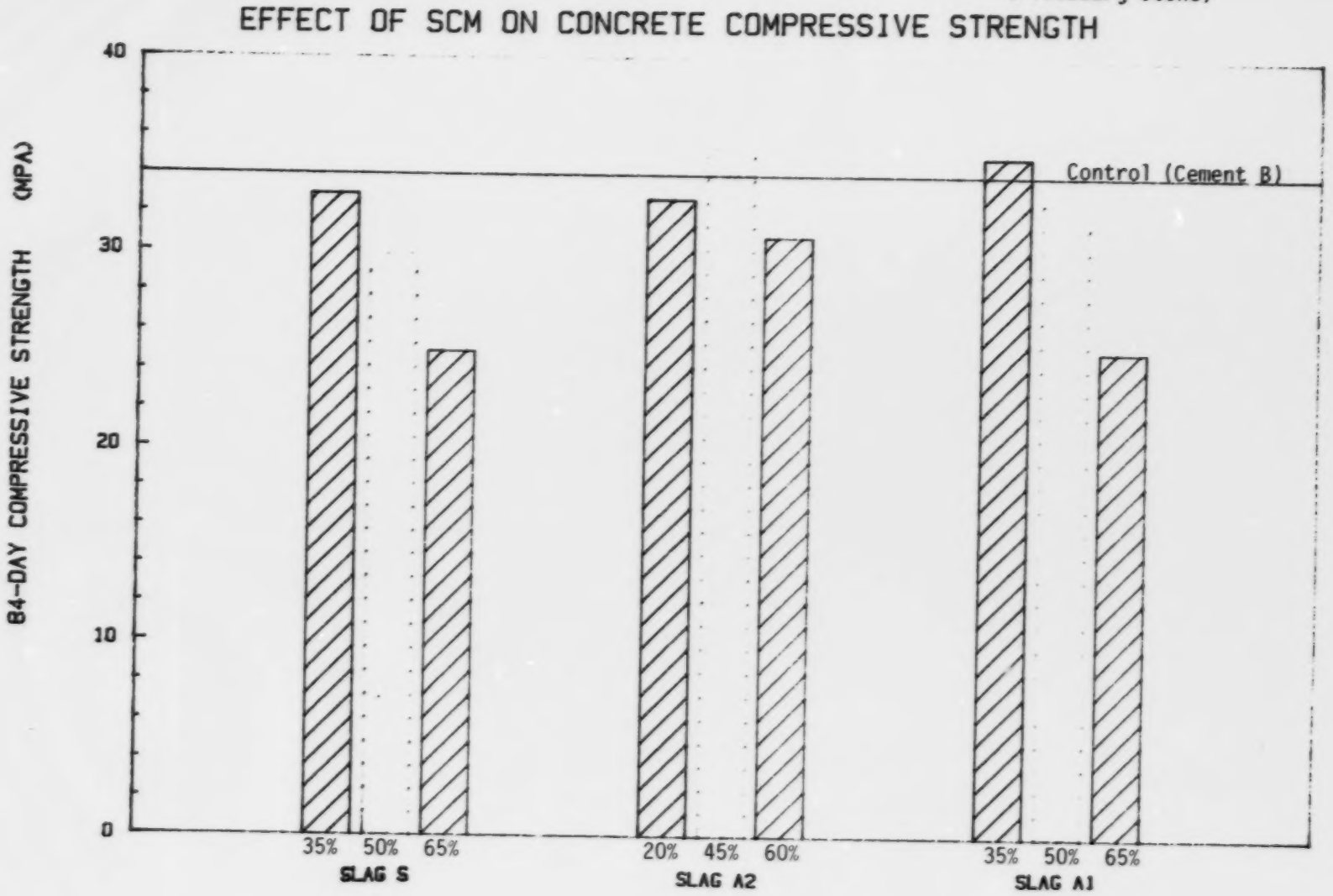


Figure 49

(Pittsburgh Stone)

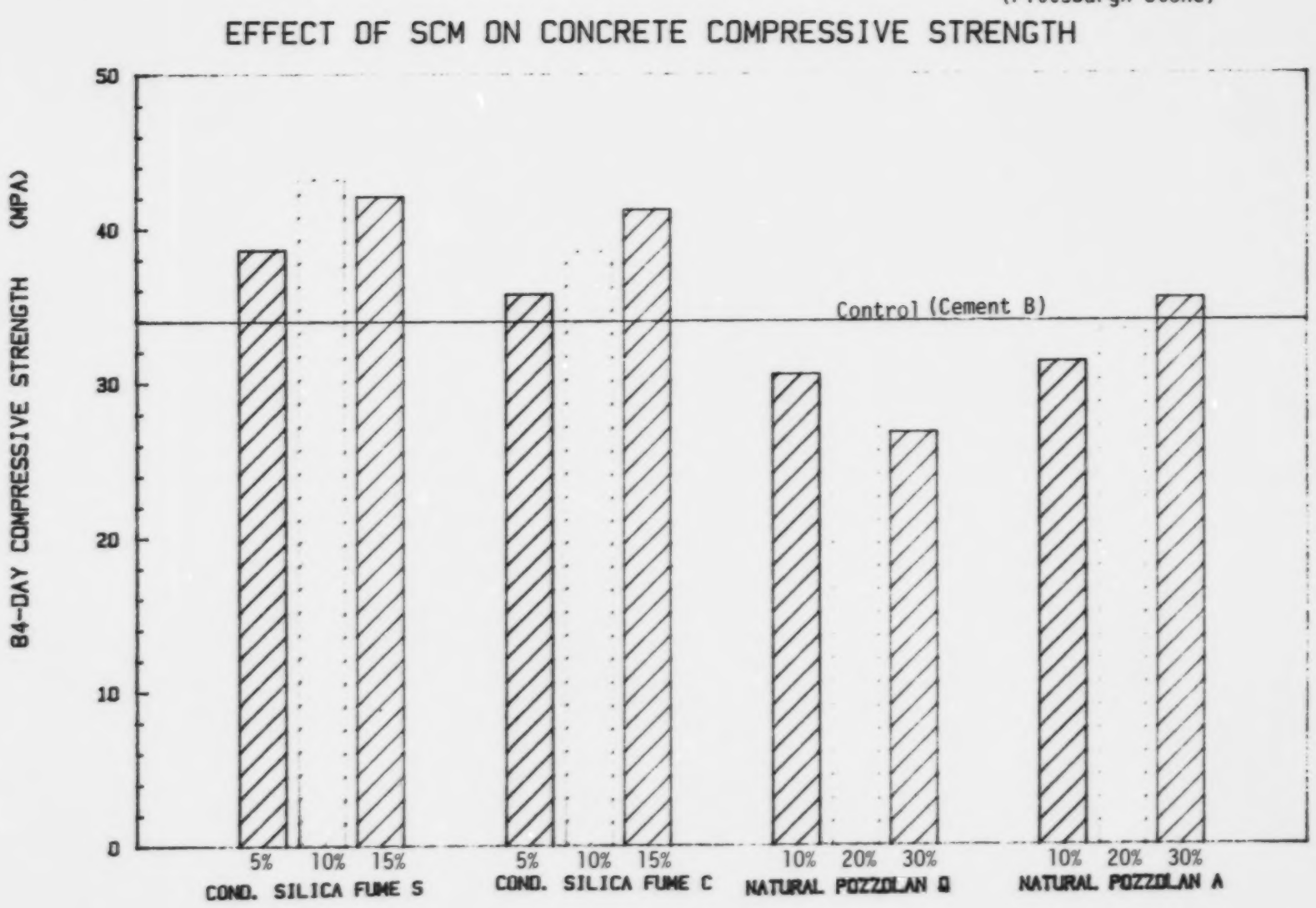
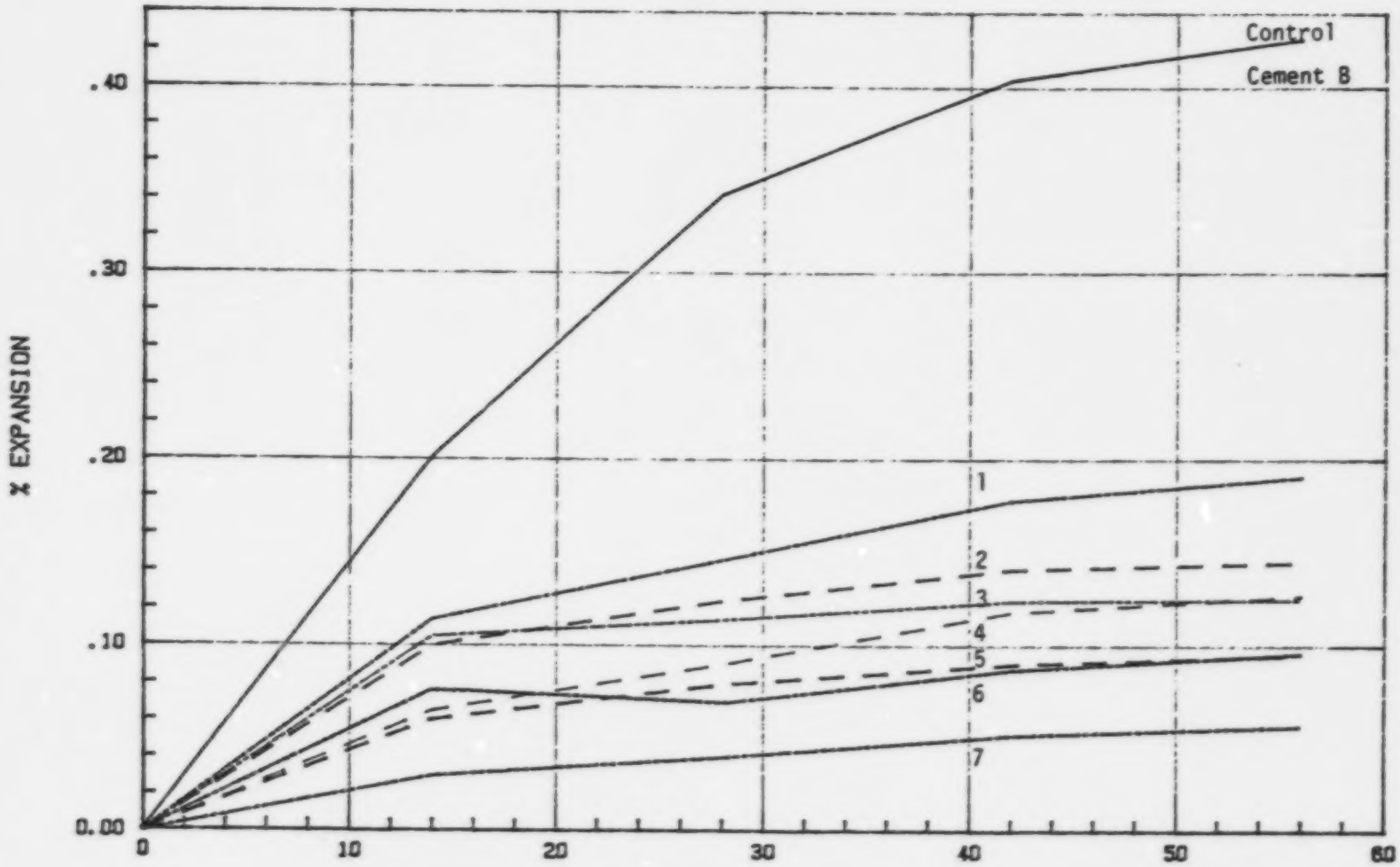
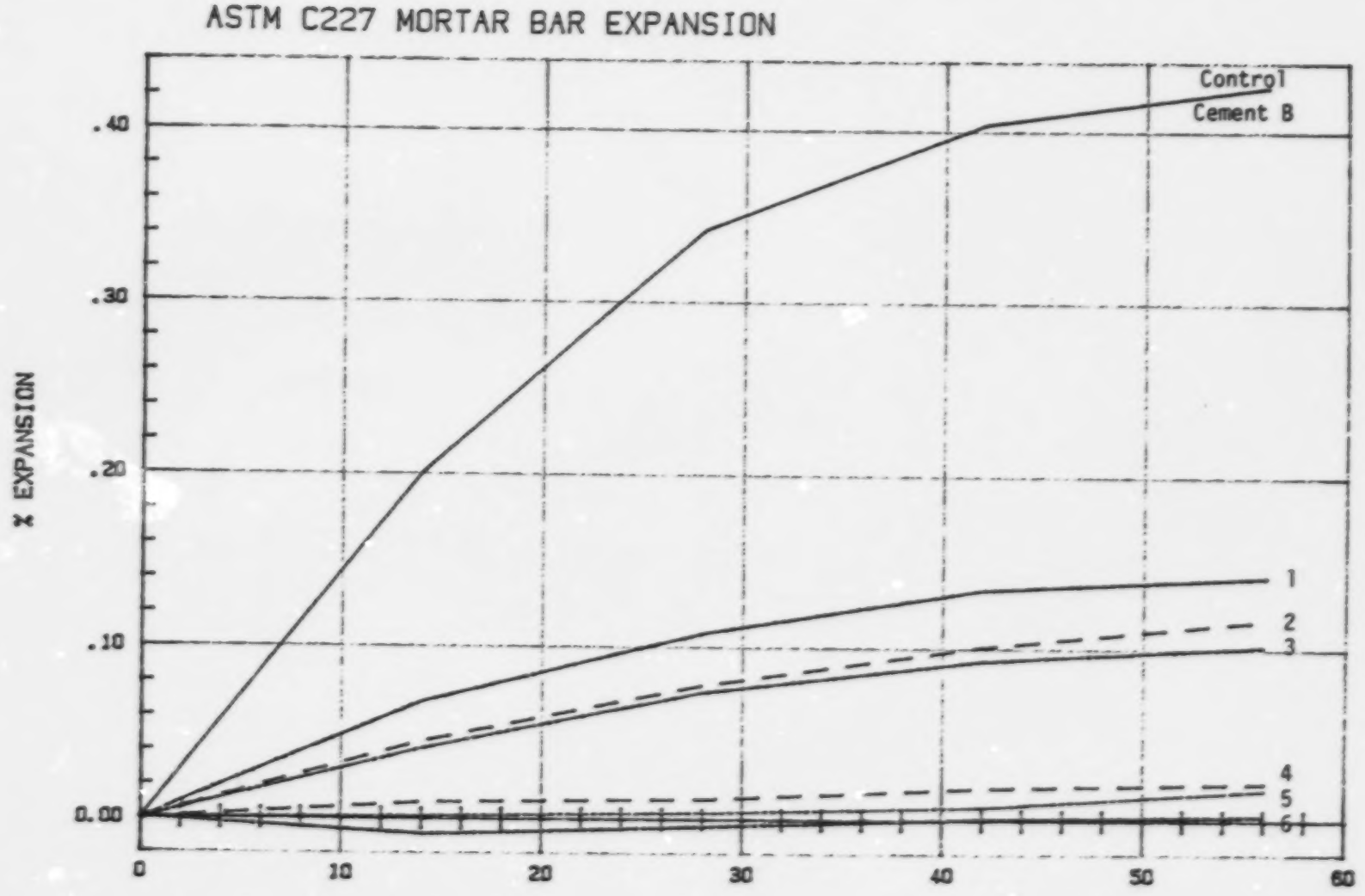


Figure 50



	Fly Ash	% Replacement by mass
1.	F	17.5
2.	S	18.4
3.	D	24.2
4.	E	20.6
5.	L1	21.4
6.	L2	20.8
7.	T	21.2

Figure 51-a



	% Replacement by mass
1. Slag A1	24.3
2. Slag S	24.0
3. Natural Pozzolan Q	22.4
4. Natural Pozzolan A	20.5
5. Cond. Silica Fume C	20.8
6. Cond. Silica Fume S	20.4

Figure 51-b

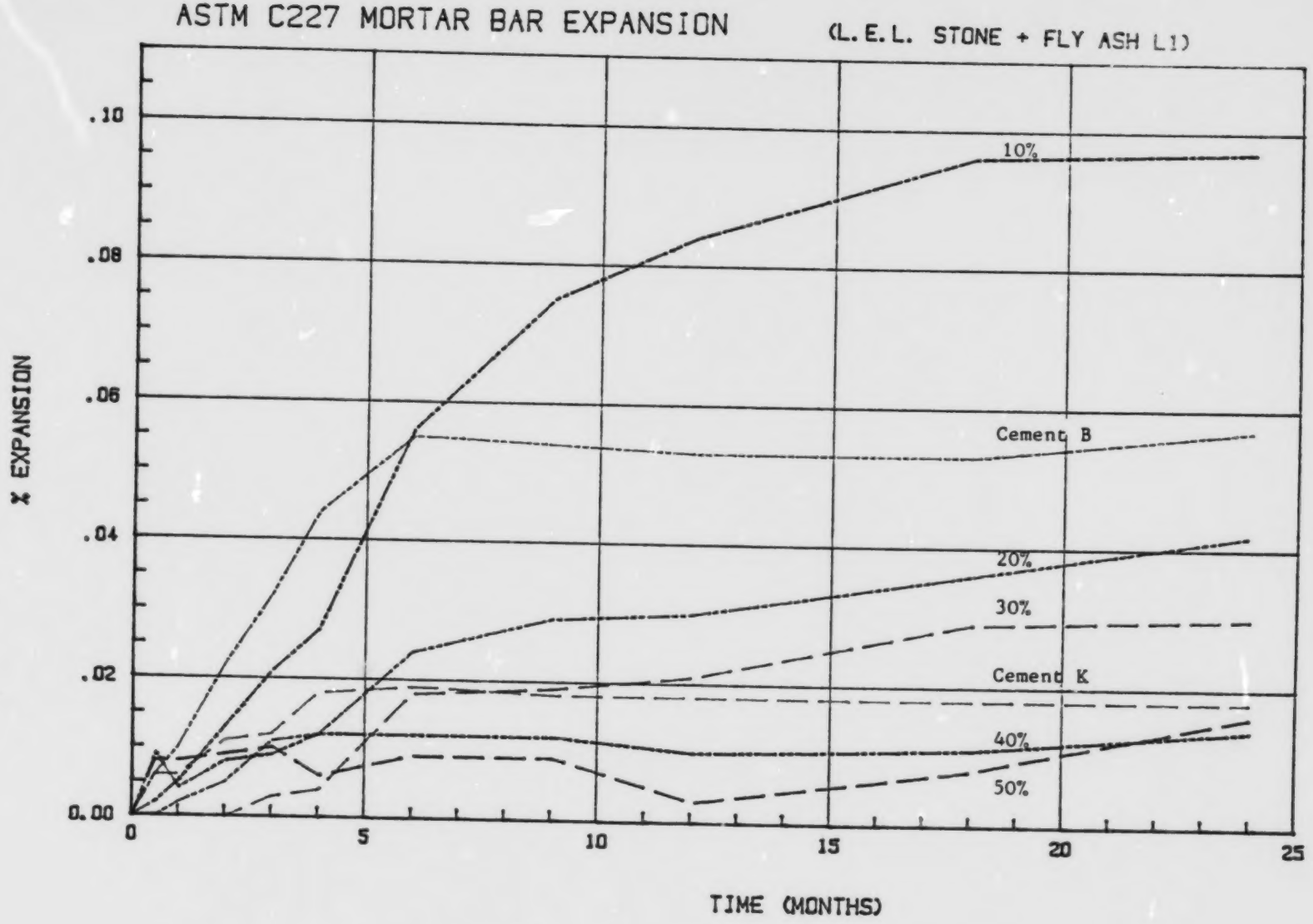

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L1)
% EXPANSION
.10
.08
.06
.04
.02
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
Cement B
20%
30%
Cement K
40%
50%

Figure 52

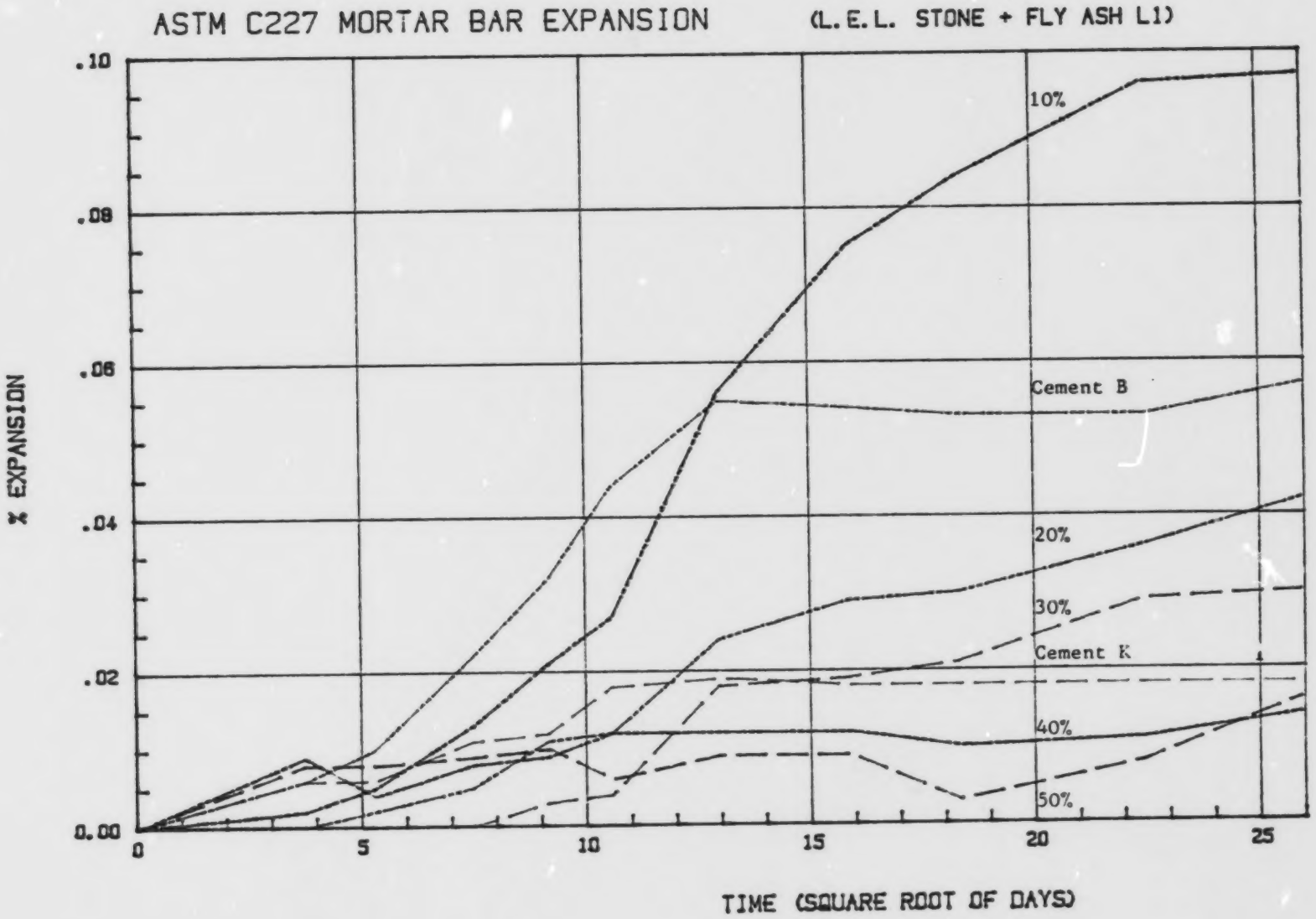

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L1)
% EXPANSION
.10
.08
.06
.04
.02
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
Cement B
20%
30%
Cement K
40%
50%

Figure 53

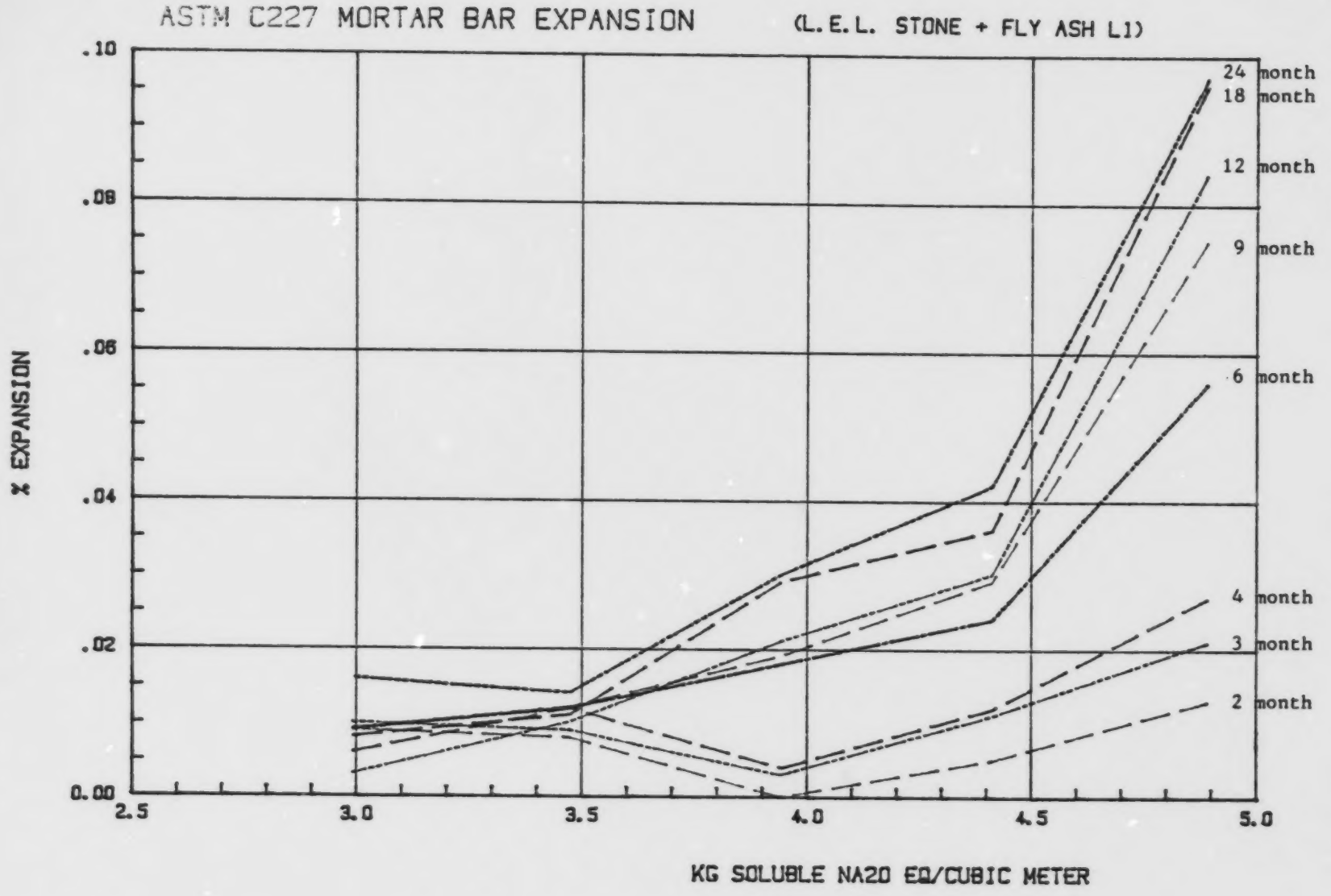
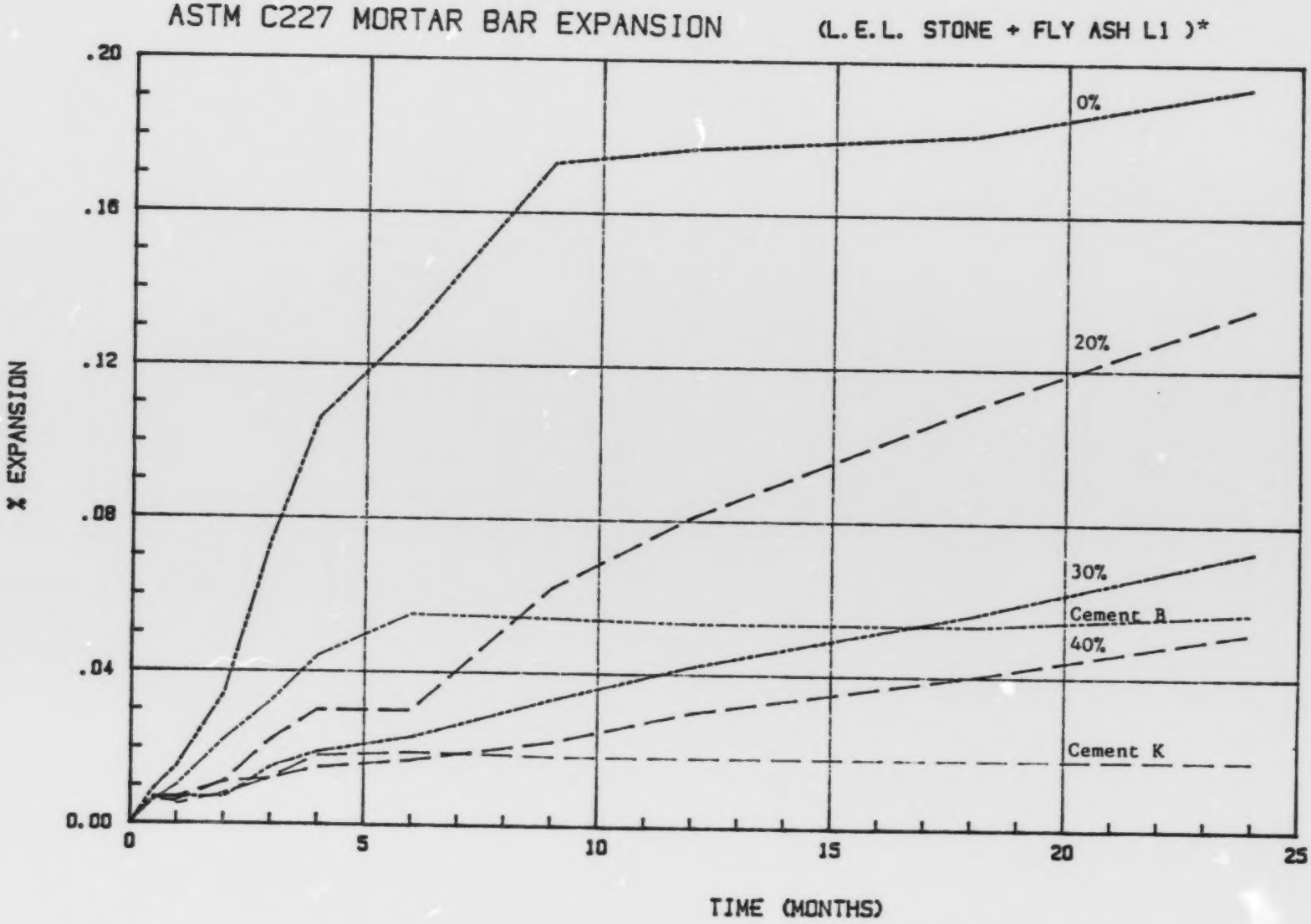
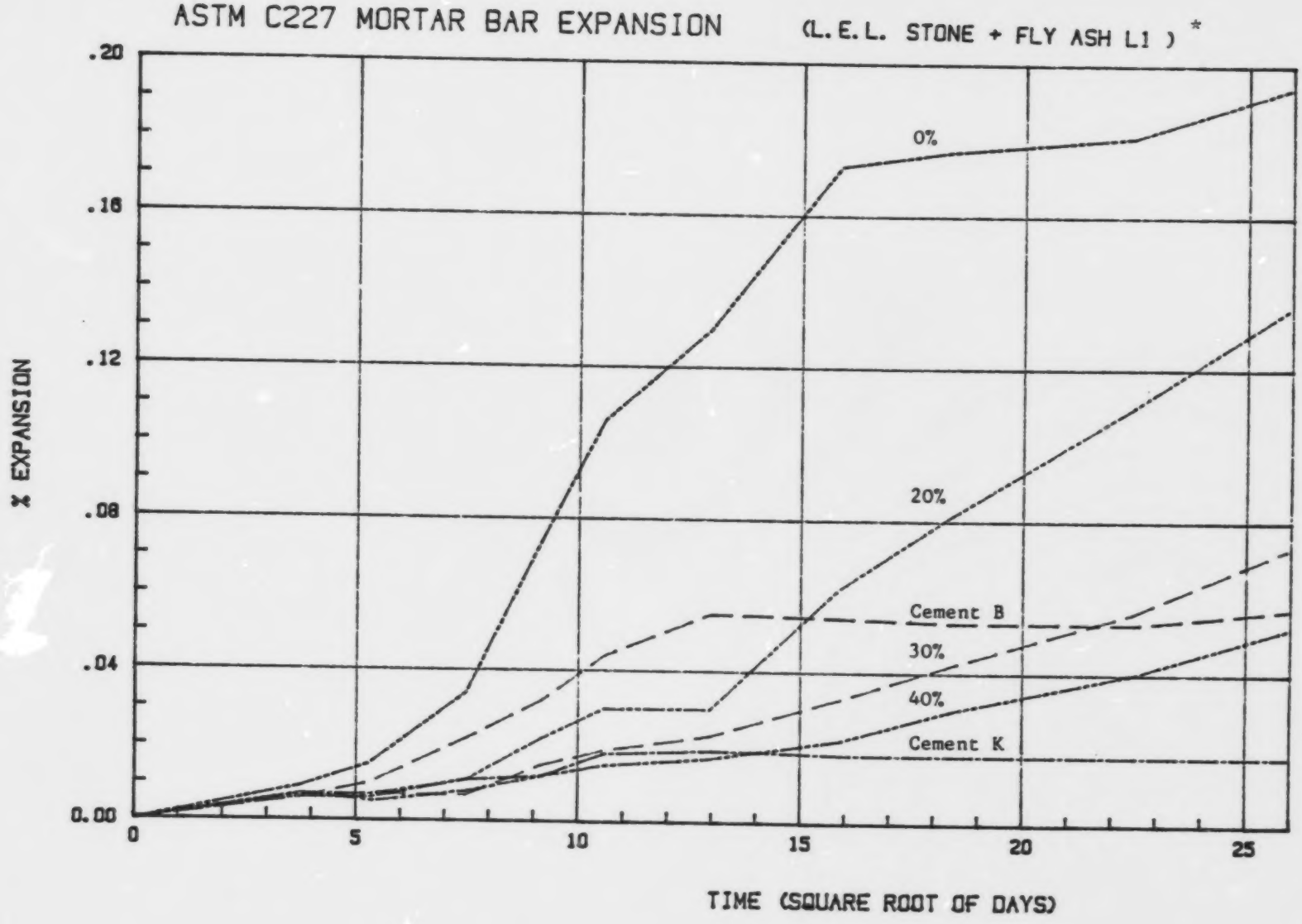

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L1)
% EXPANSION
.10
.08
.06
.04
.02
0.00
2.5
3.0
3.5
4.0
4.5
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 54



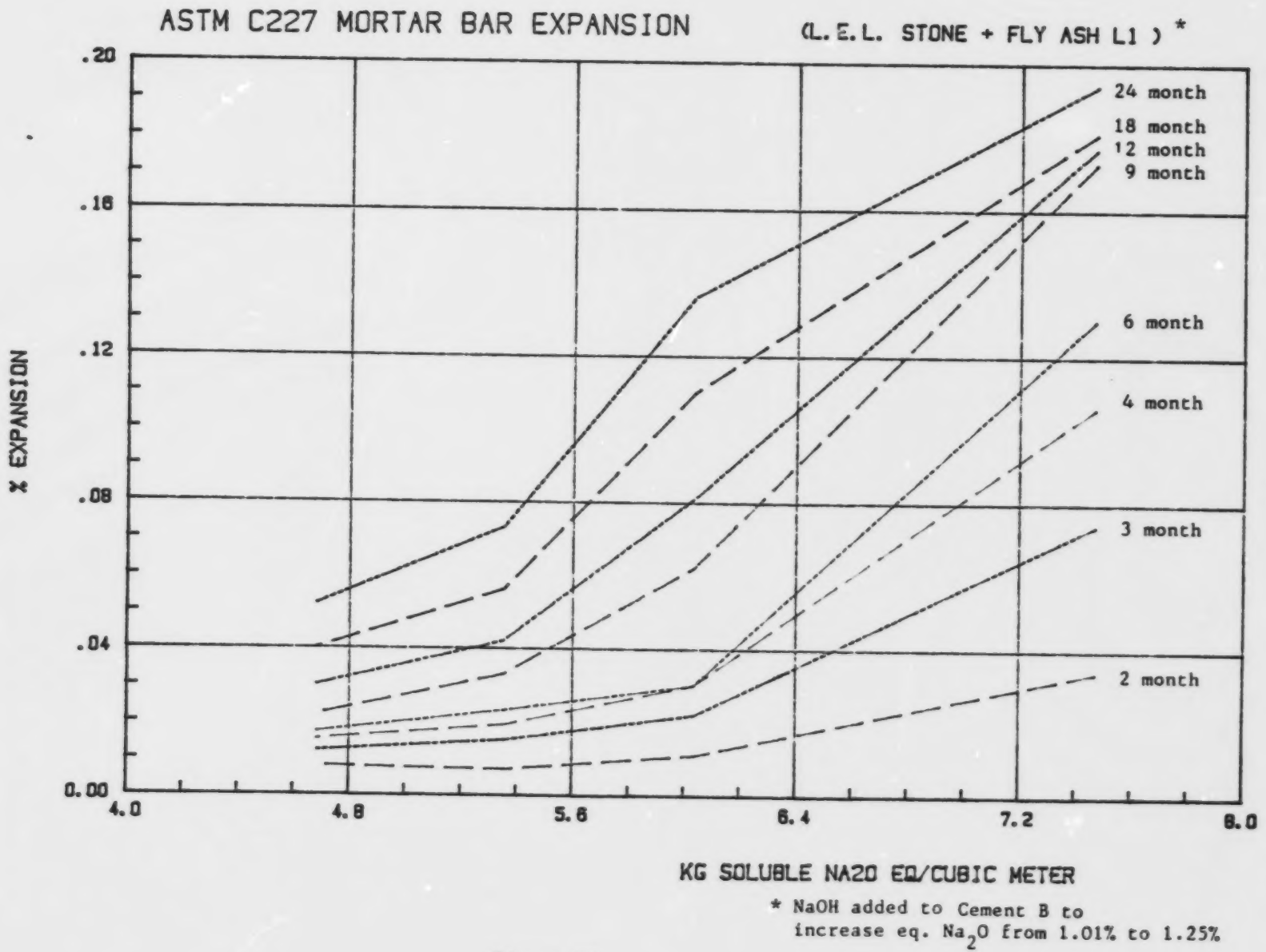
* NaOH added to Cement B to increase eq. Na_2O from 1.01% to 1.25%

Figure 55



* NaOH added to Cement B to increase eq. Na_2O from 1.01% to 1.25%

Figure 56



* NaOH added to Cement B to increase eq. Na_2O from 1.01% to 1.25%

Figure 57

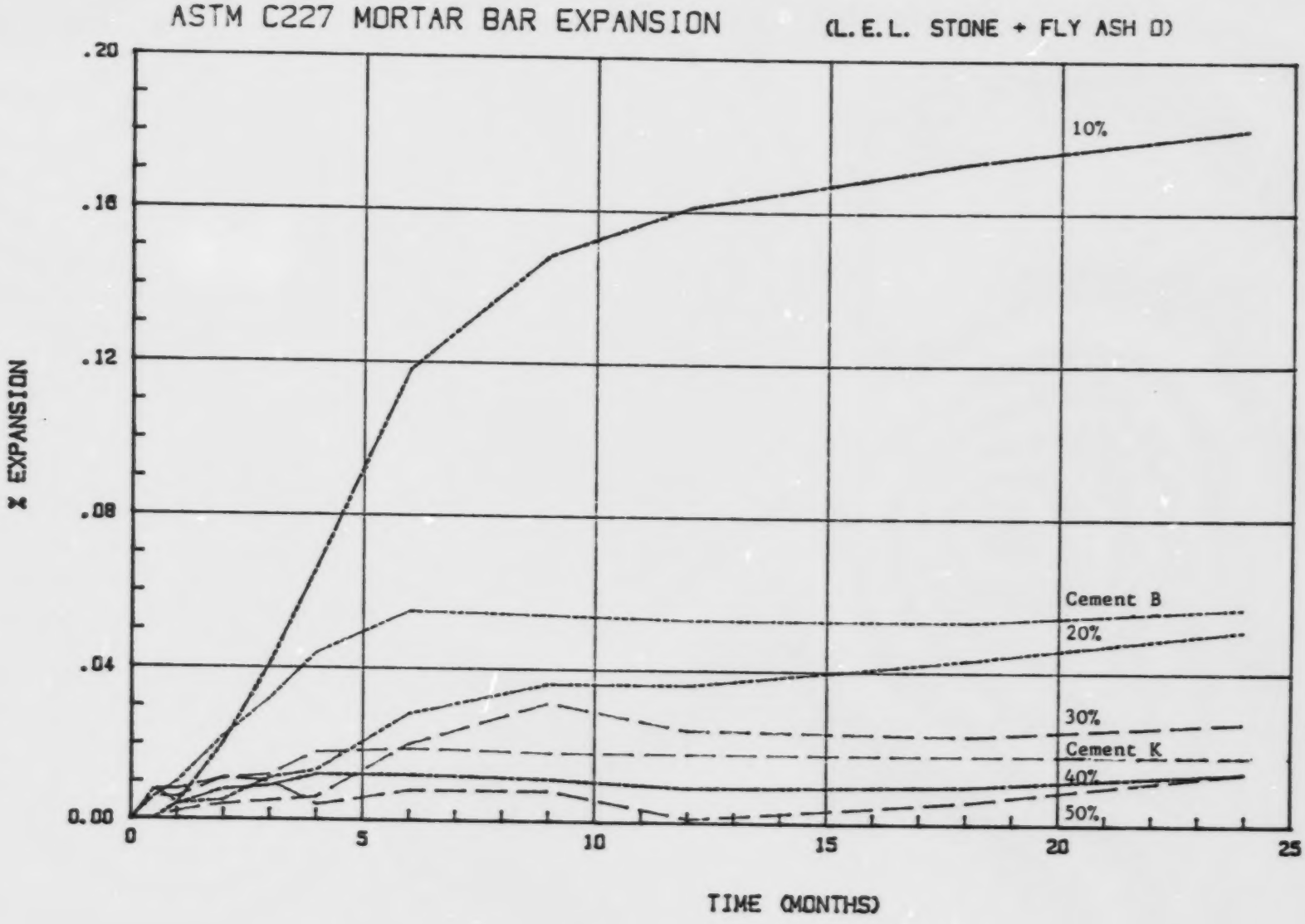

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH D)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
Cement B
20%
30%
Cement K
40%
50%

Figure 58

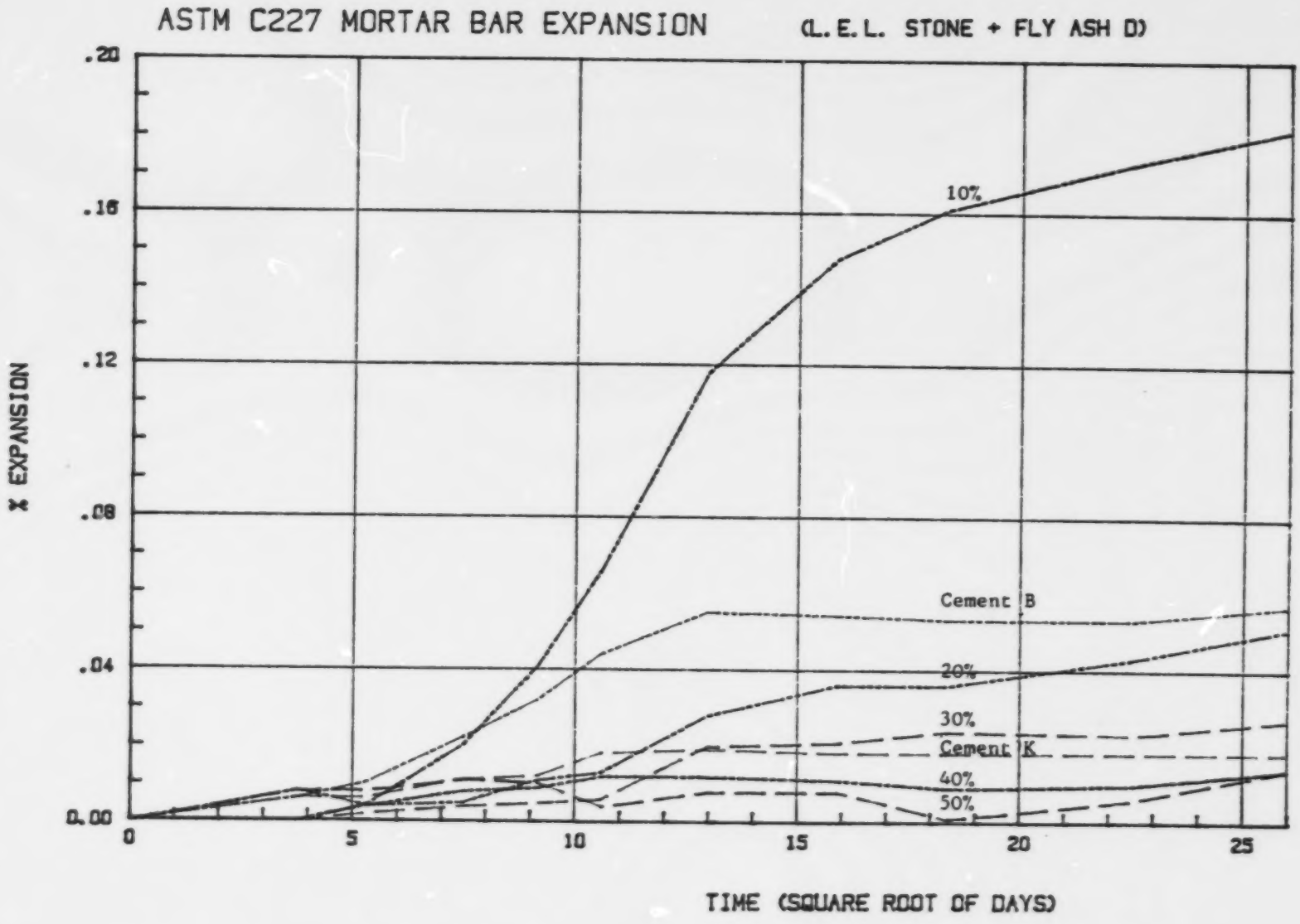

ASTM C227 MORTAR BAR EXPANSION
(L. E. L. STONE + FLY ASH D)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
Cement B
20%
30%
Cement K
40%
50%

Figure 59

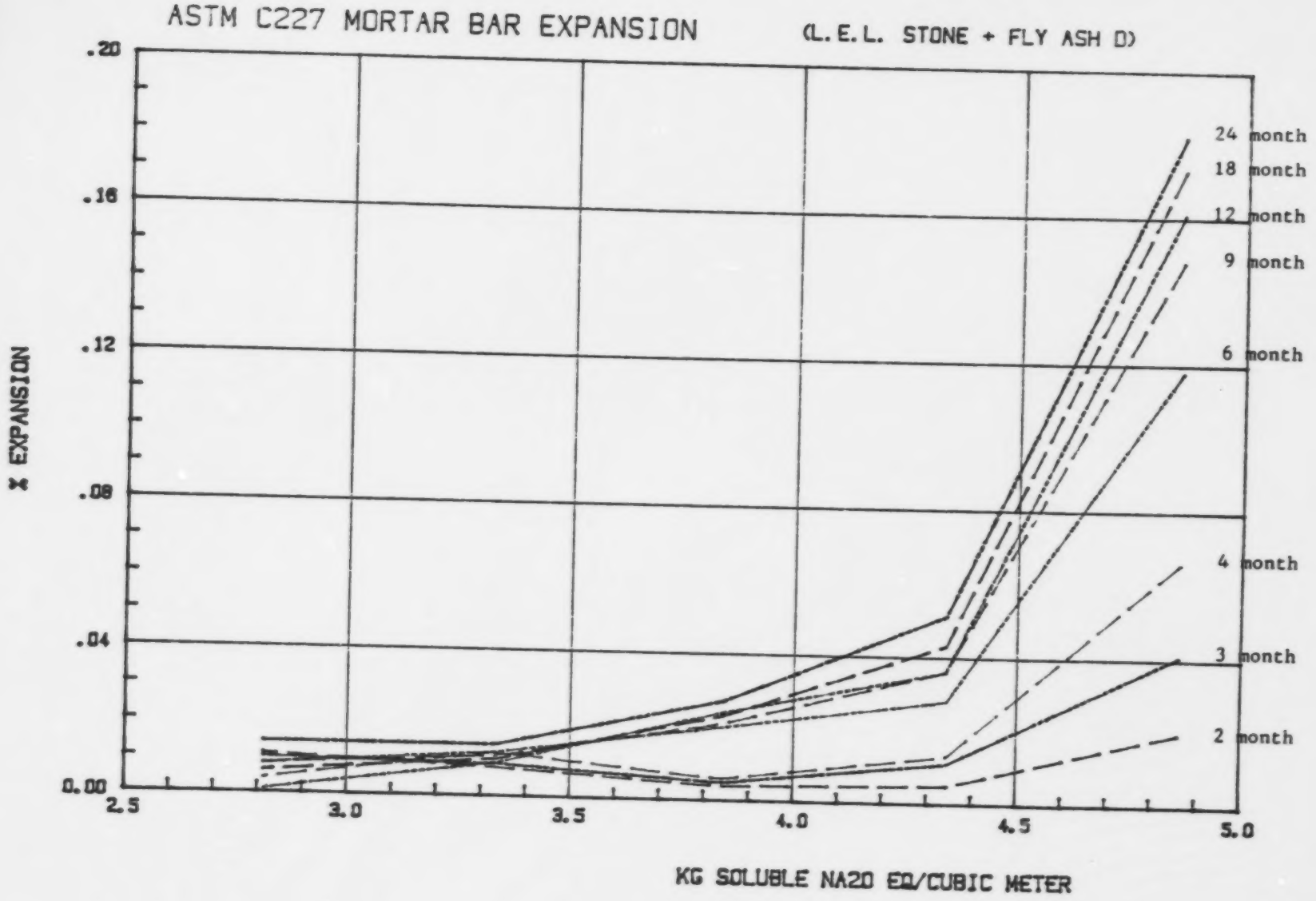

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH D)
% EXPANSION
.20
.16
.12
.08
.04
0.00
2.5
3.0
3.5
4.0
4.5
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 60

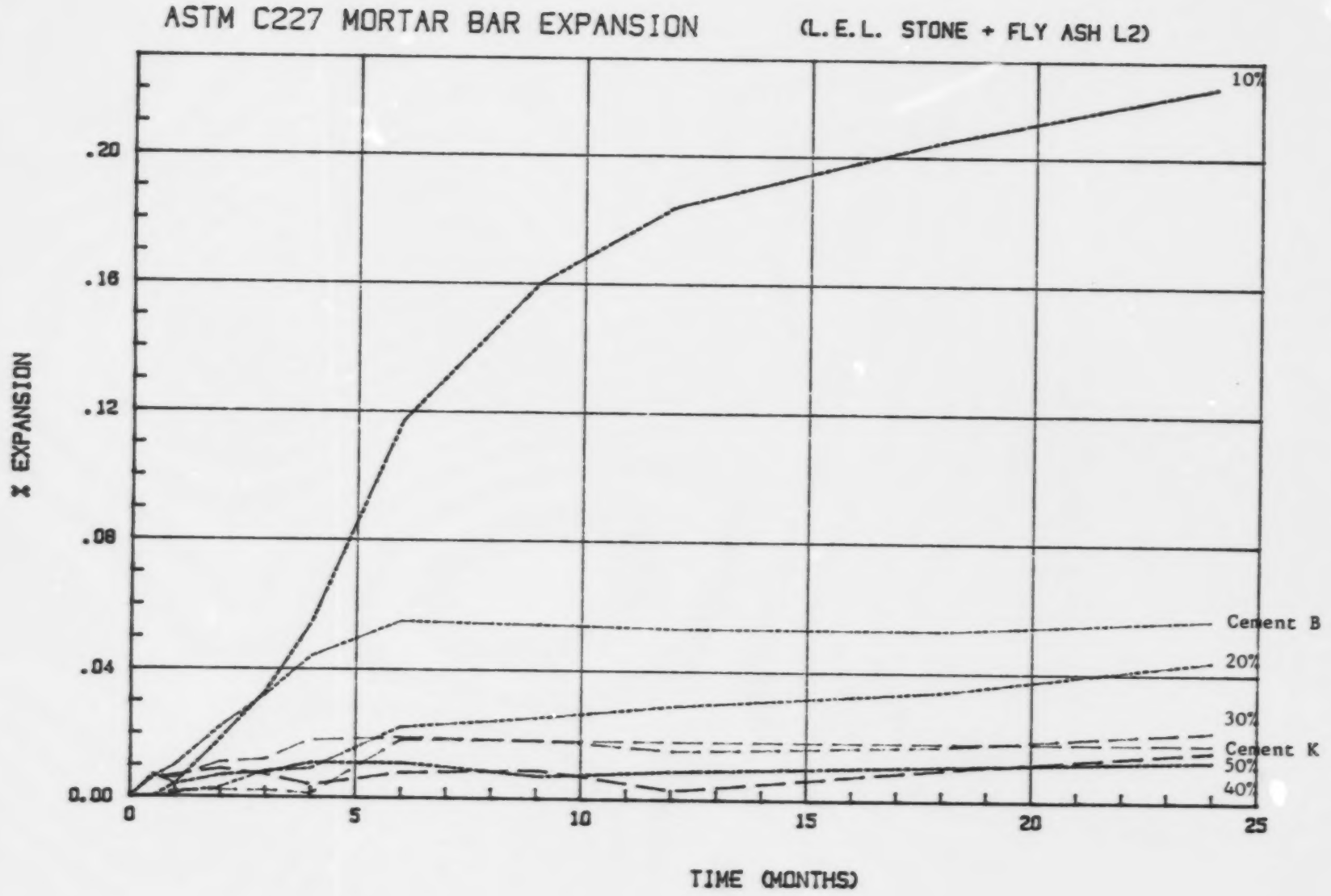

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L2)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
Cement B
20%
30%
Cement K
50%
40%

Figure 61

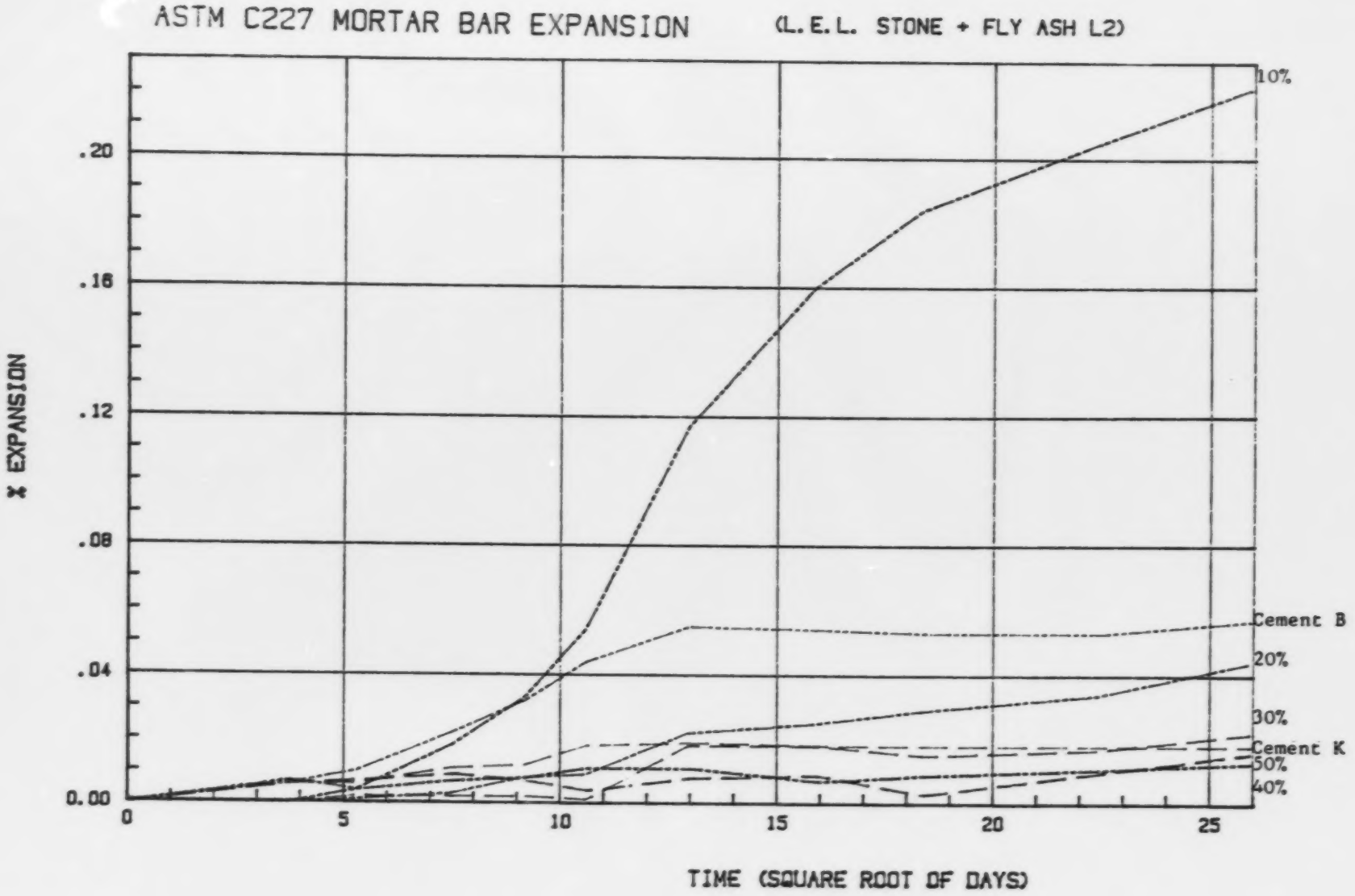

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L2)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
Cement B
20%
30%
Cement K
50%
40%

Figure 62

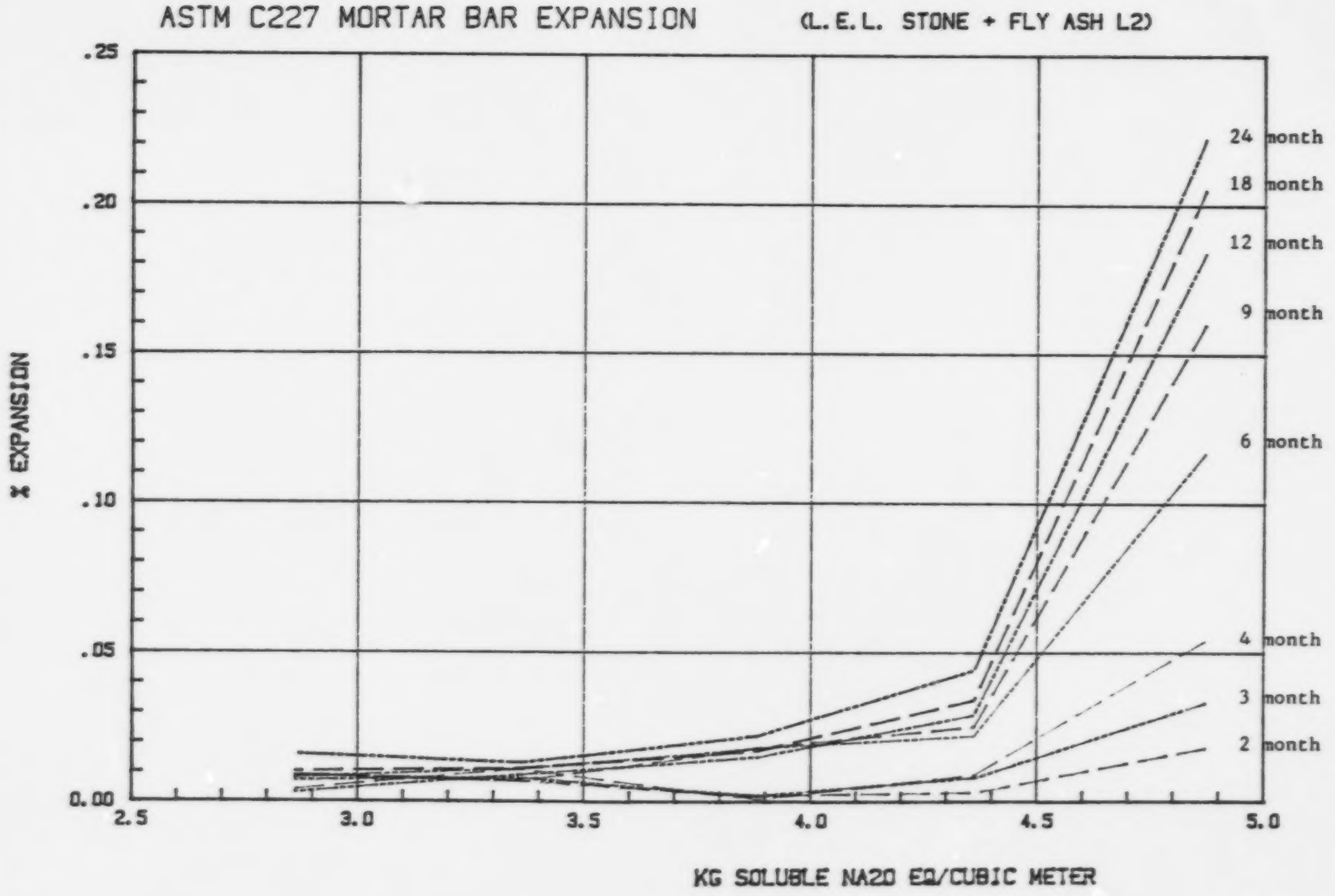

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH L2)
% EXPANSION
.25
.20
.15
.10
.05
0.00
2.5
3.0
3.5
4.0
4.5
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 63

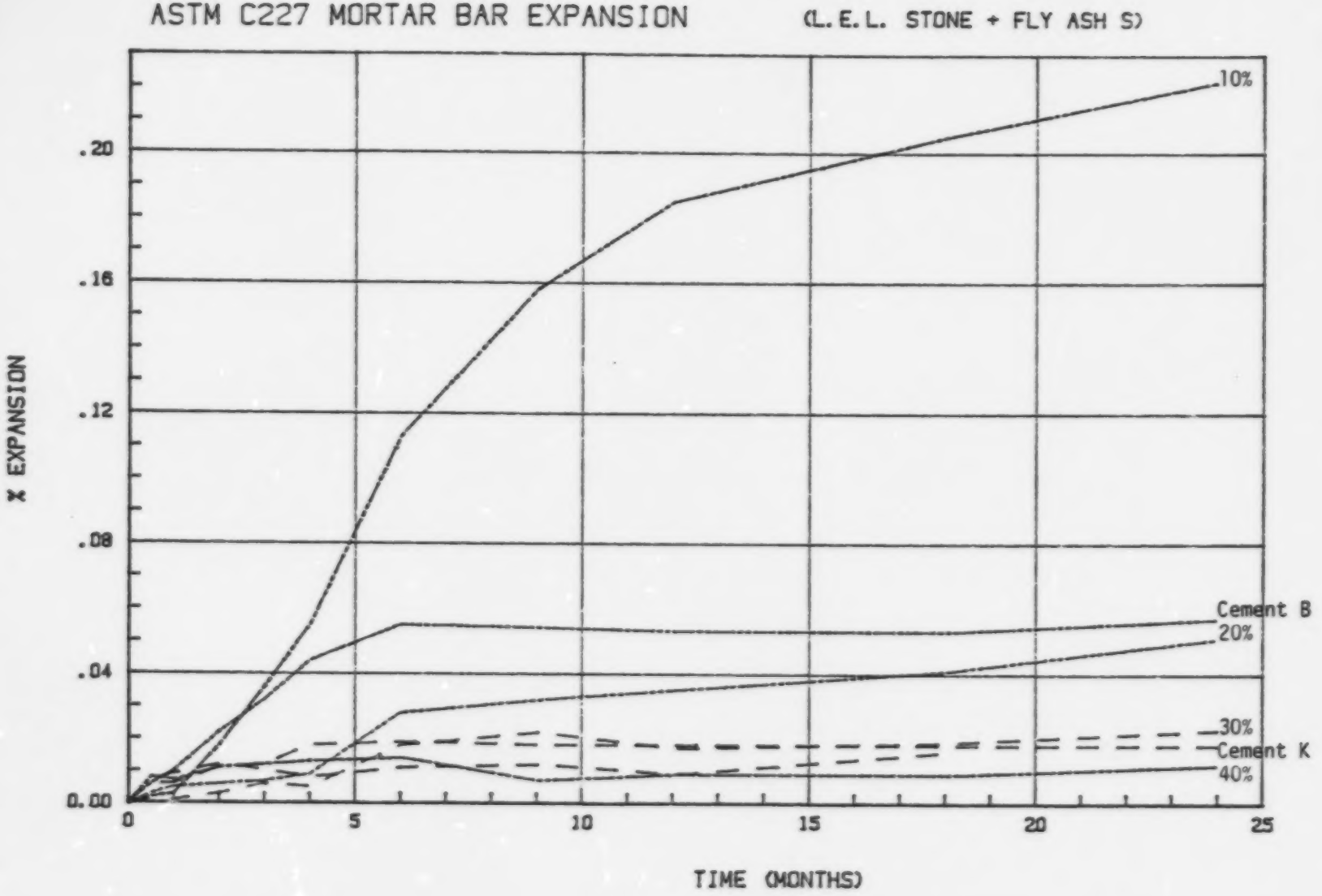

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH S)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
Cement B
20%
30%
Cement K
40%

Figure 64

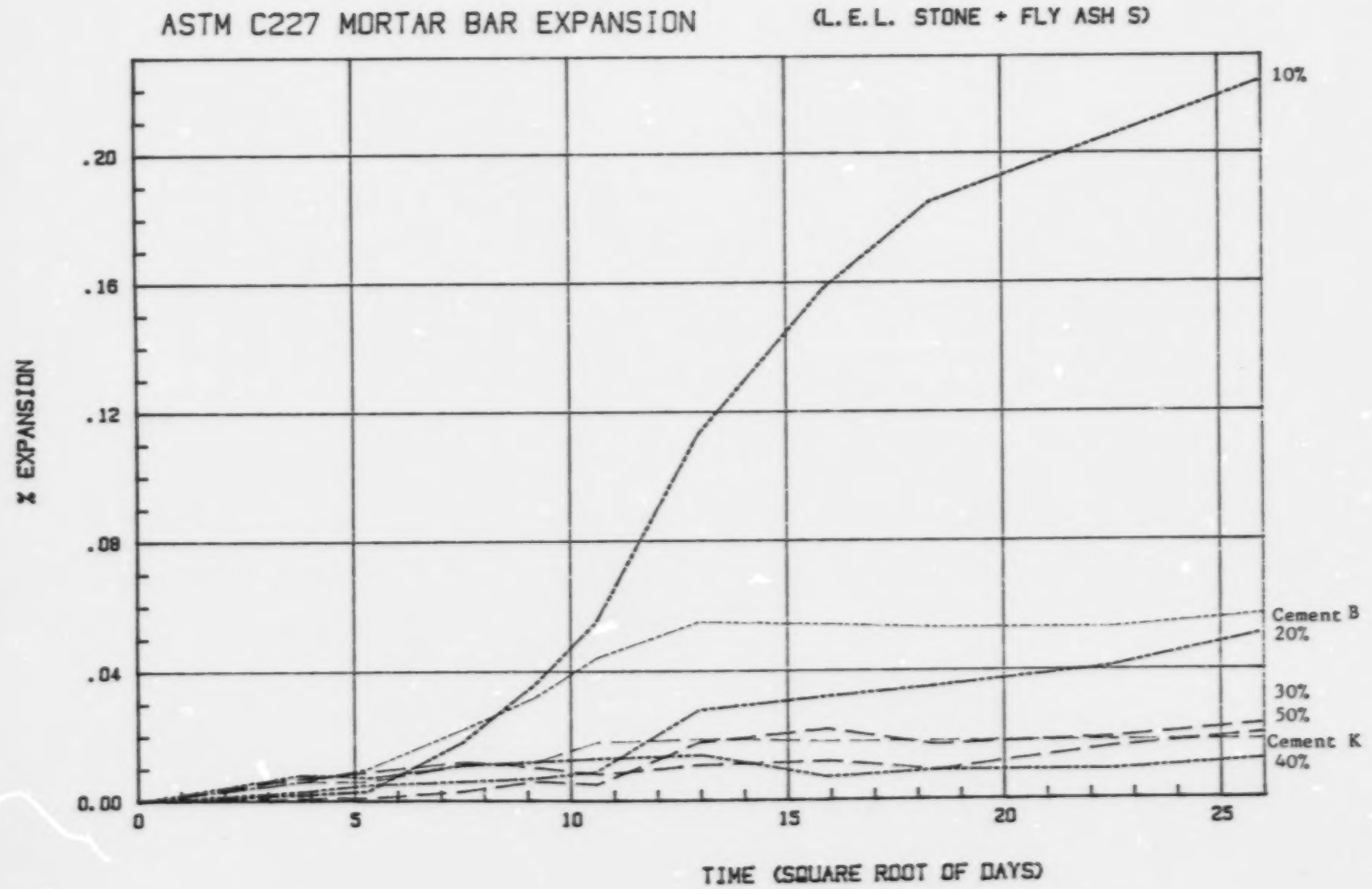

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH S)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
Cement B
20%
30%
50%
Cement K
40%

Figure 65

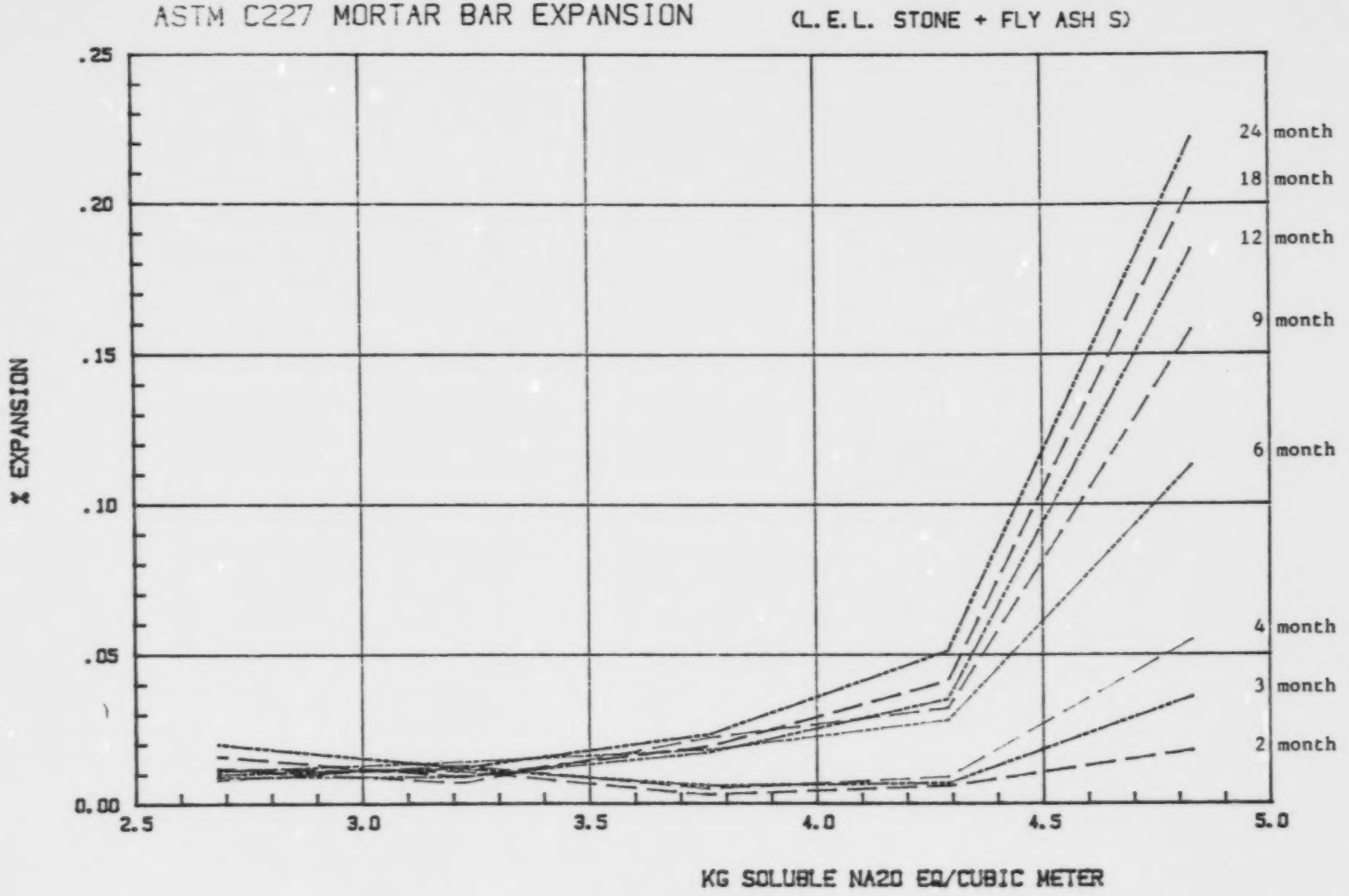

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH S)
% EXPANSION
.25
.20
.15
.10
.05
0.00
2.5
3.0
3.5
4.0
4.5
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 66

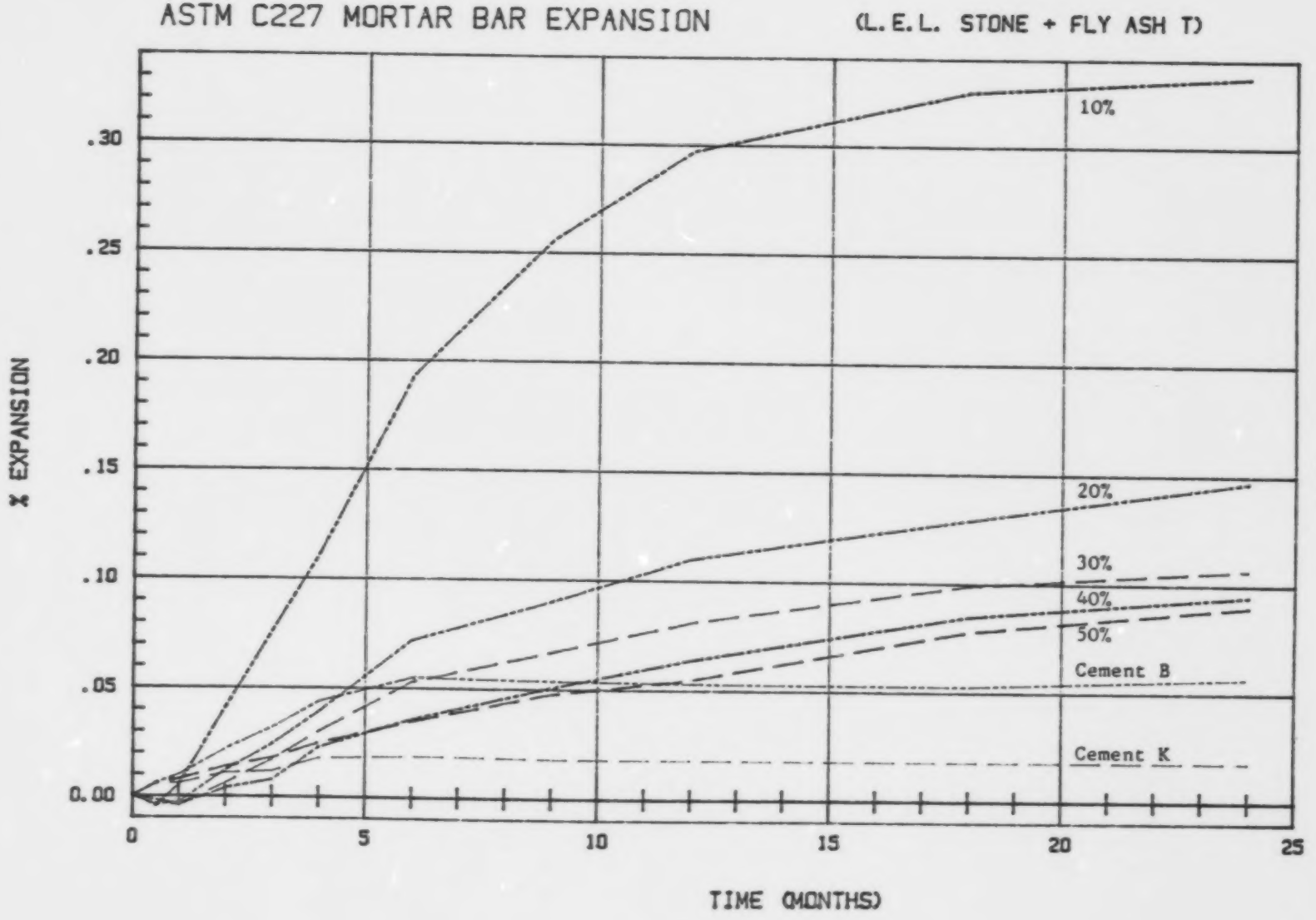

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH T)
% EXPANSION
.30
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
20%
30%
40%
50%
Cement B
Cement K

Figure 67

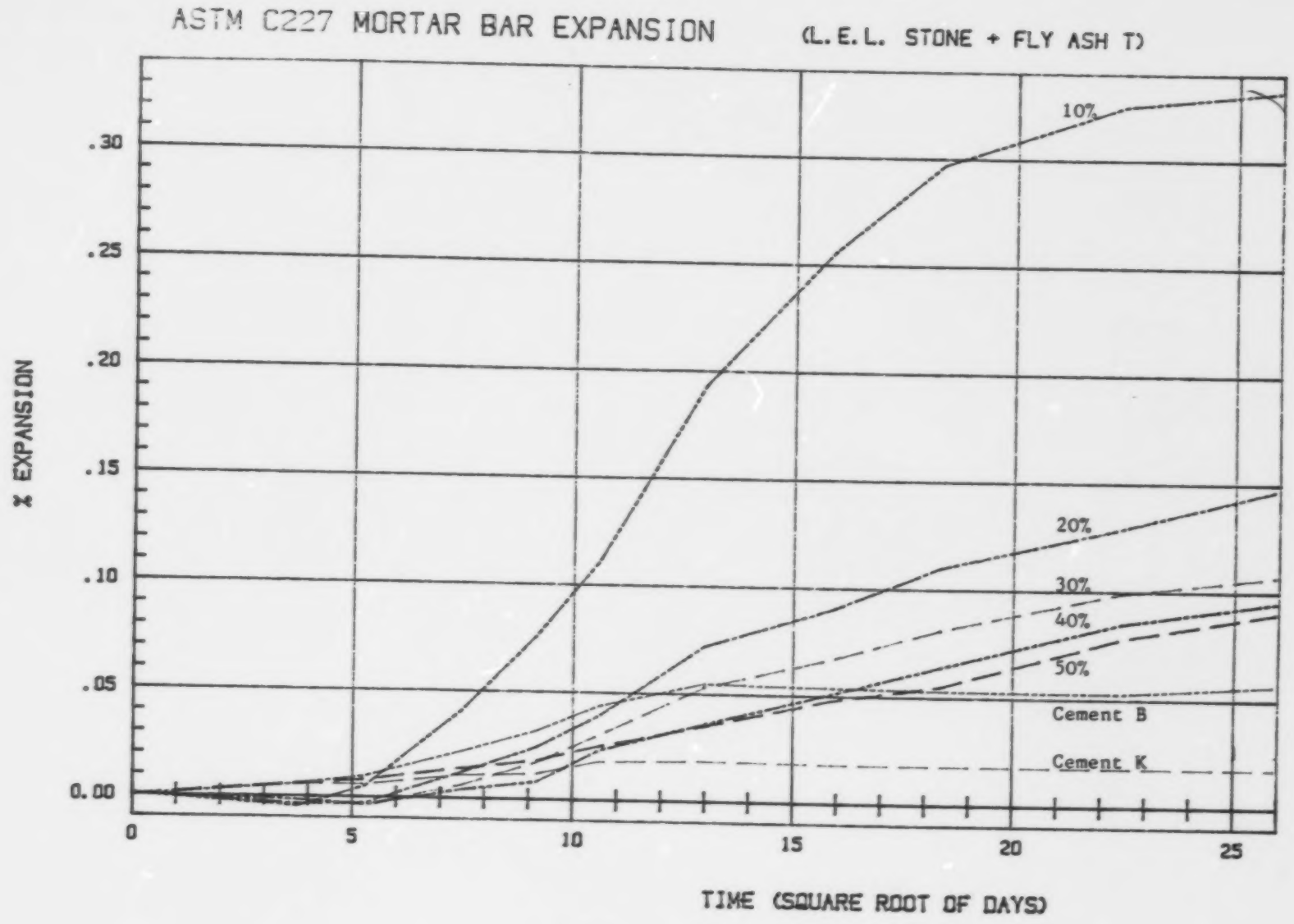

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH T)
% EXPANSION
.30
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
20%
30%
40%
50%
Cement B
Cement K

Figure 68

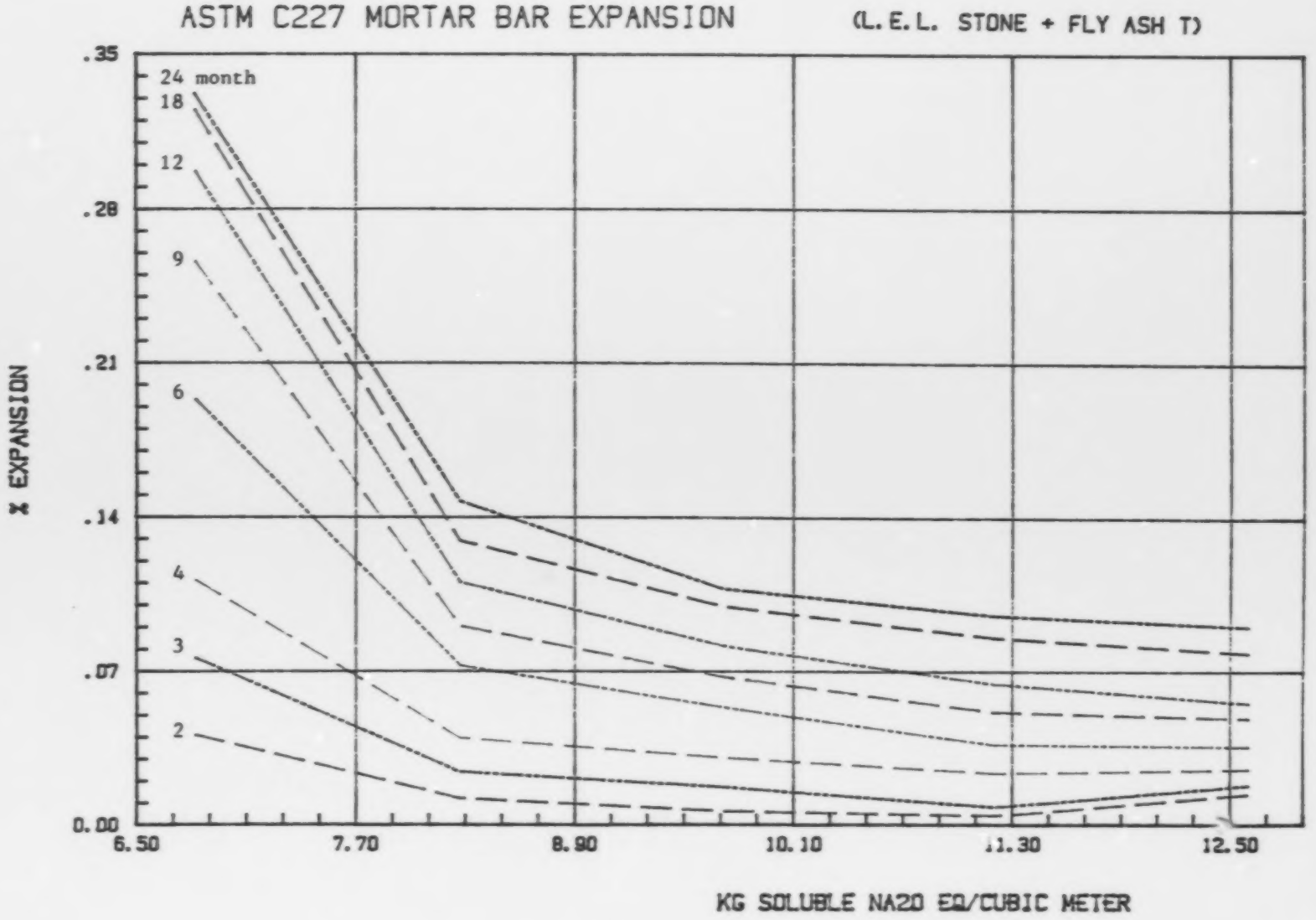

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH T)
% EXPANSION
.35
.28
.21
.14
.07
0.00
24 month
18
12
9
6
4
3
2
6.50
7.70
8.90
10.10
11.30
12.50
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 69

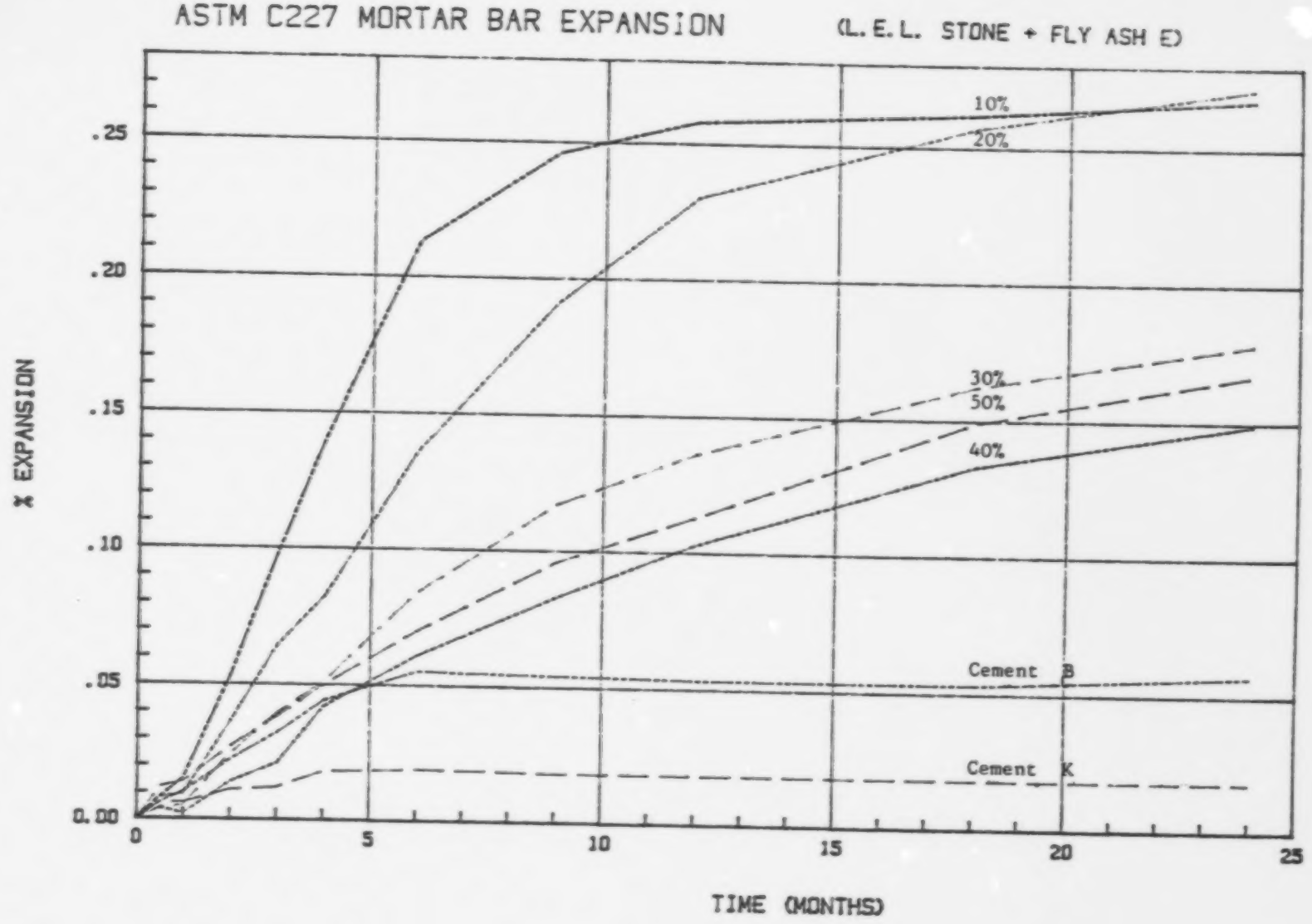

ASTM C227 MORTAR BAR EXPANSION
(L. E. L. STONE + FLY ASH E)
% EXPANSION
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
20%
30%
50%
40%
Cement B
Cement K

Figure 70

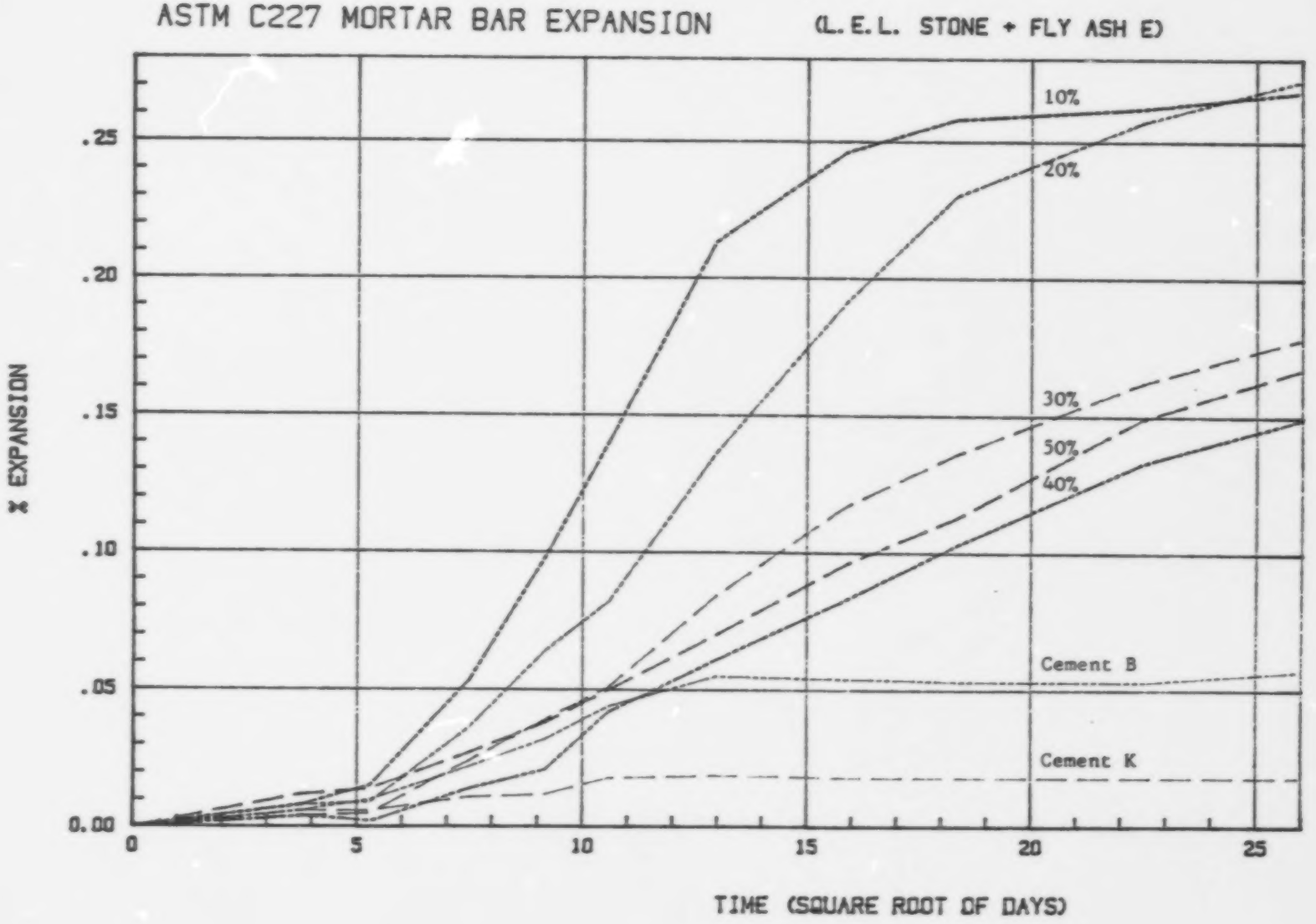

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH E)
% EXPANSION
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
20%
30%
50%
40%
Cement B
Cement K

Figure 71

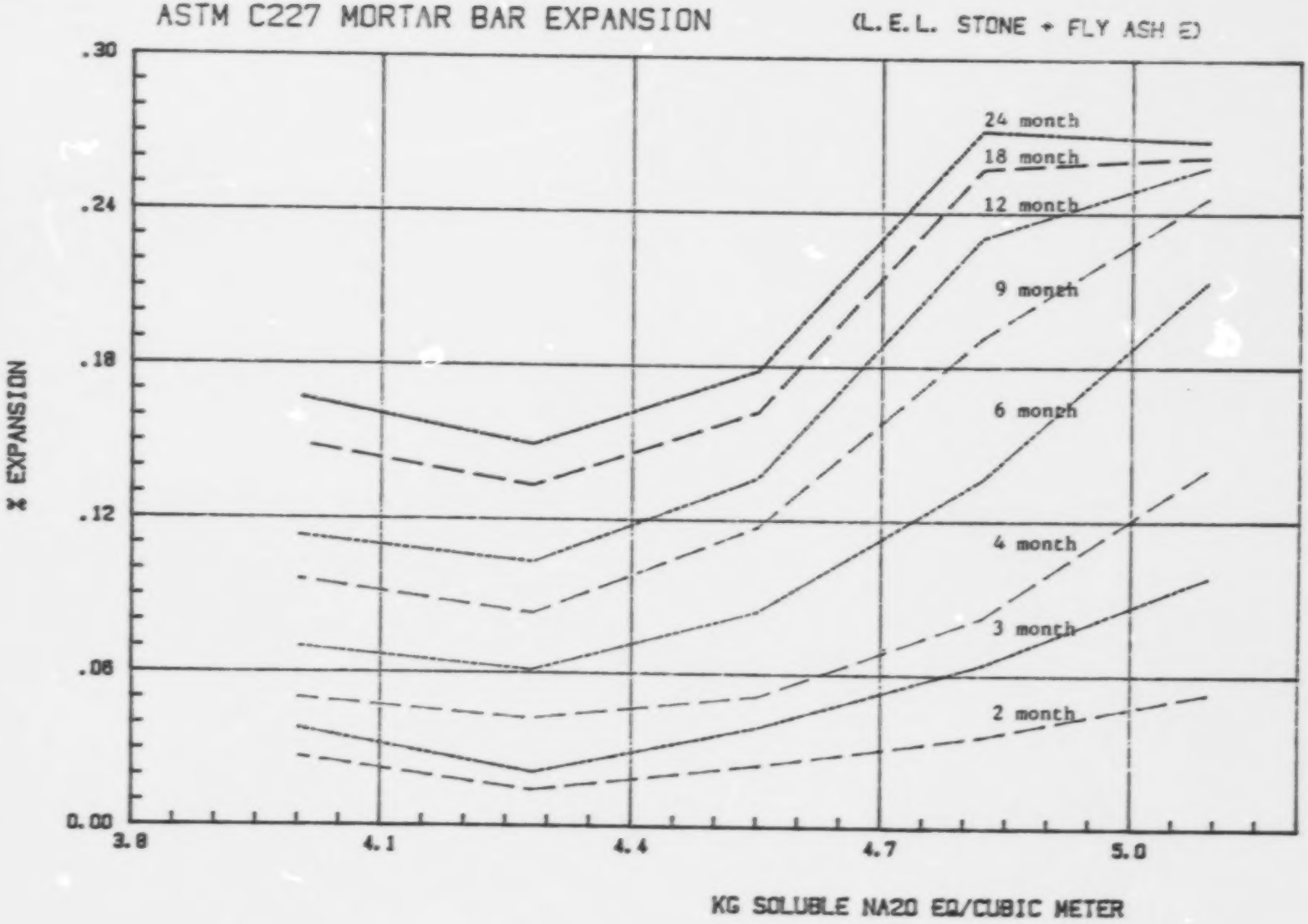

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH E)
.30
.24
.18
.12
.06
0.00
% EXPANSION
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month
3.8
4.1
4.4
4.7
5.0
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 72

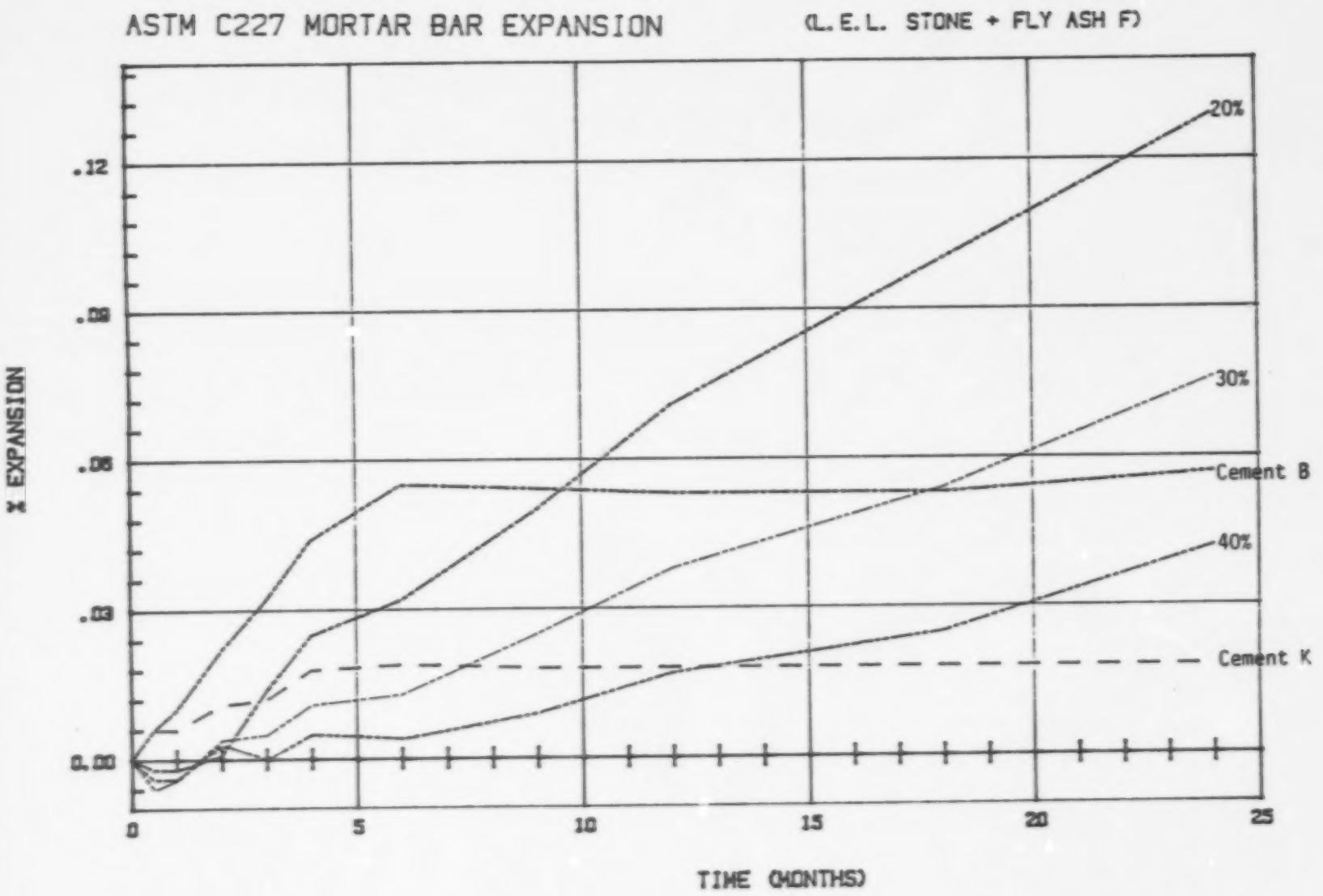

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH F)
20%
30%
Cement B
40%
Cement K
.12
.08
.06
.03
0.00
% EXPANSION
0
5
10
15
20
25
TIME (MONTHS)

Figure 73

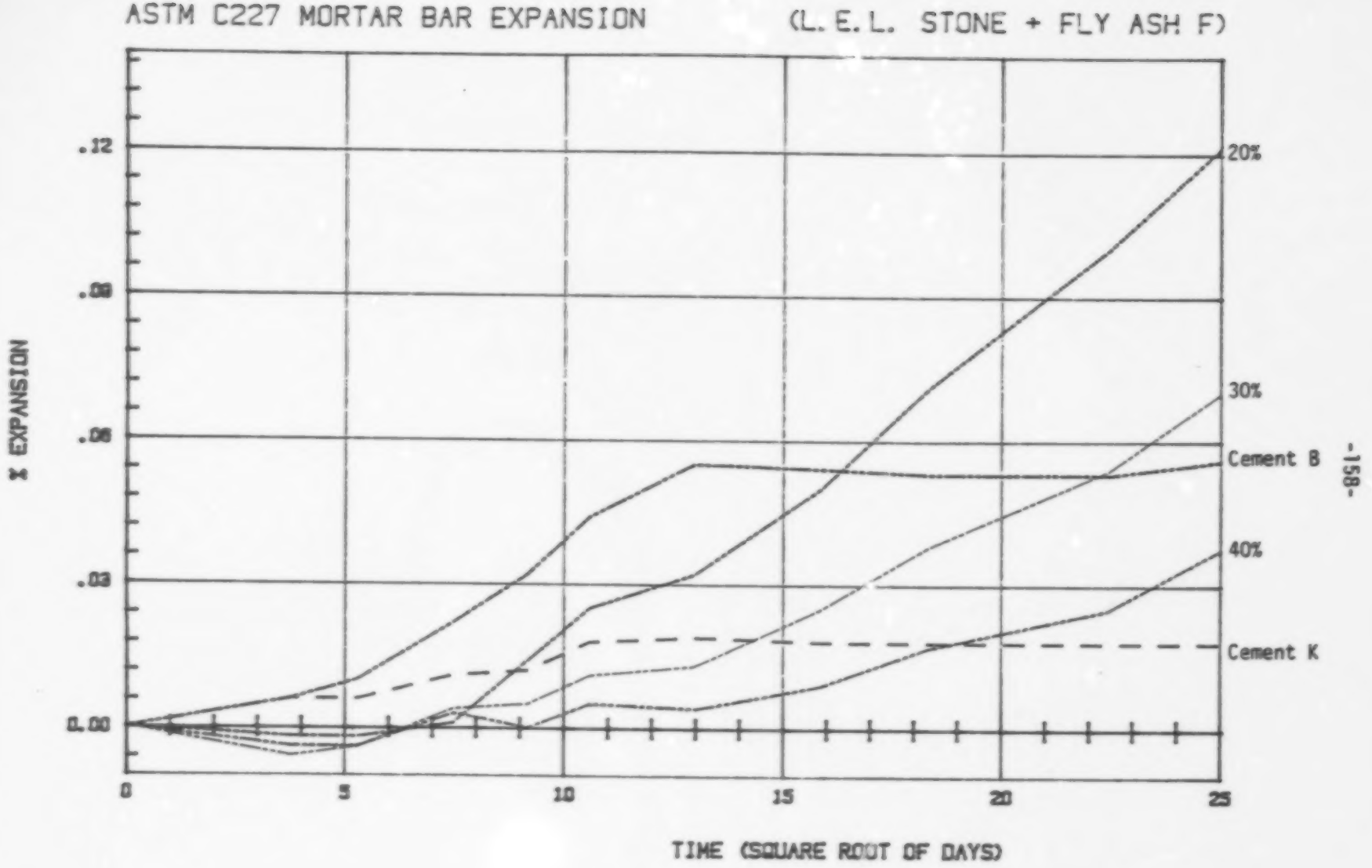

ASTM C227 MORTAR BAR EXPANSION
(L. E. L. STONE + FLY ASH F)
% EXPANSION
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
20%
30%
Cement B
40%
Cement K

Figure 74

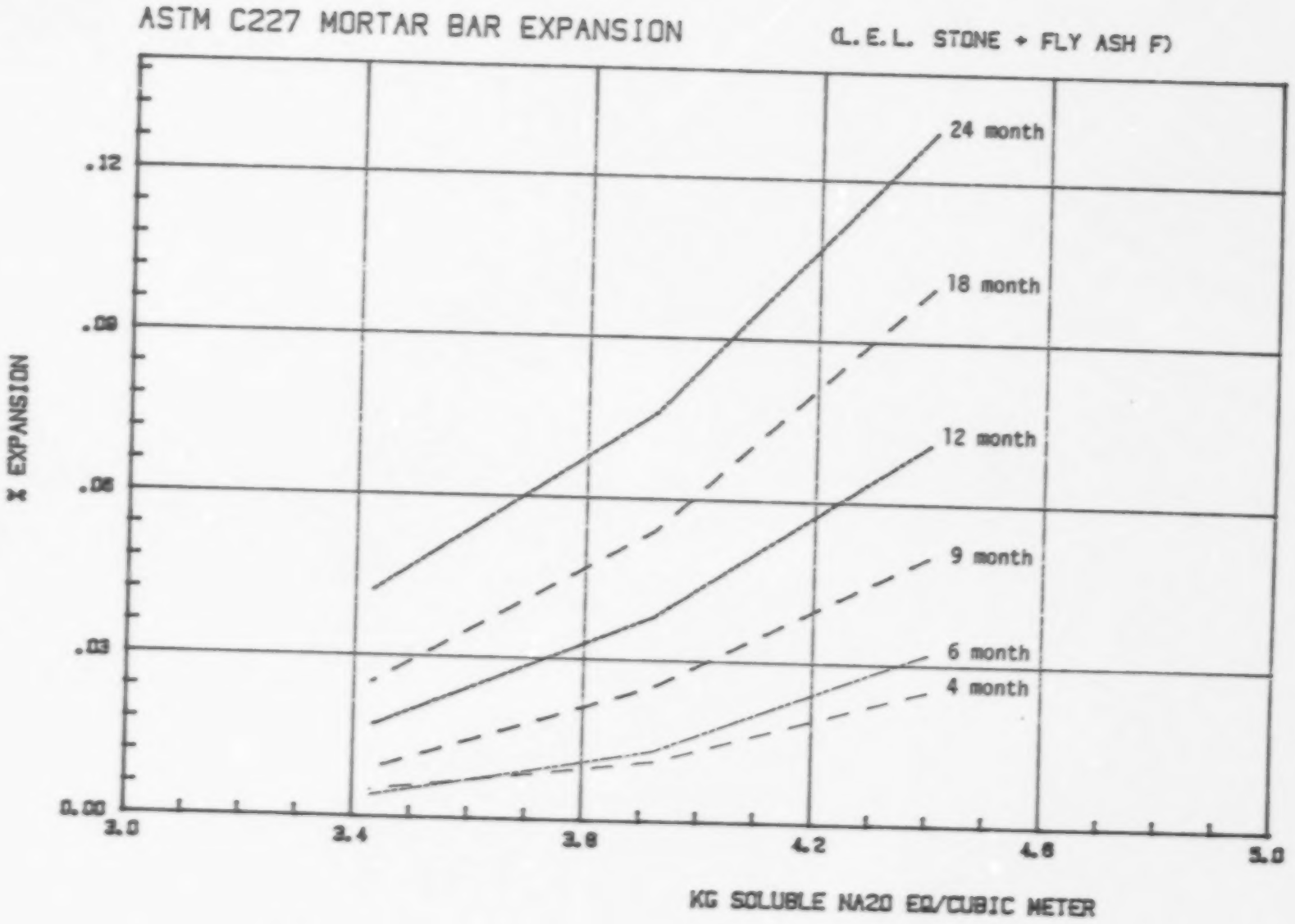

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH F)
24 month
18 month
12 month
9 month
6 month
4 month
% EXPANSION
.12
.09
.06
.03
0.00
3.0
3.4
3.8
4.2
4.6
5.0
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 75

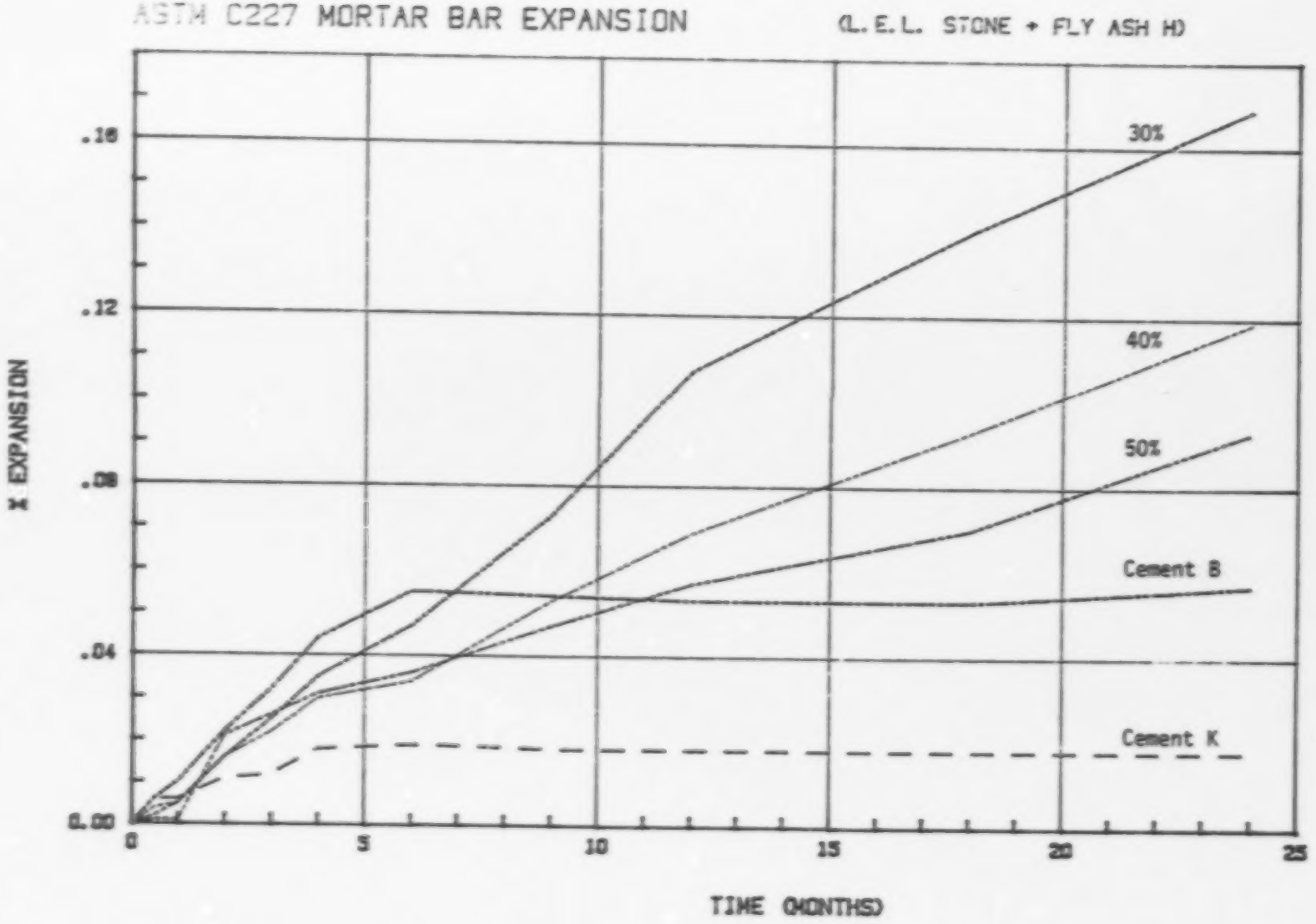

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH H)
% EXPANSION
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (MONTHS)
30%
40%
50%
Cement B
Cement K

Figure 76

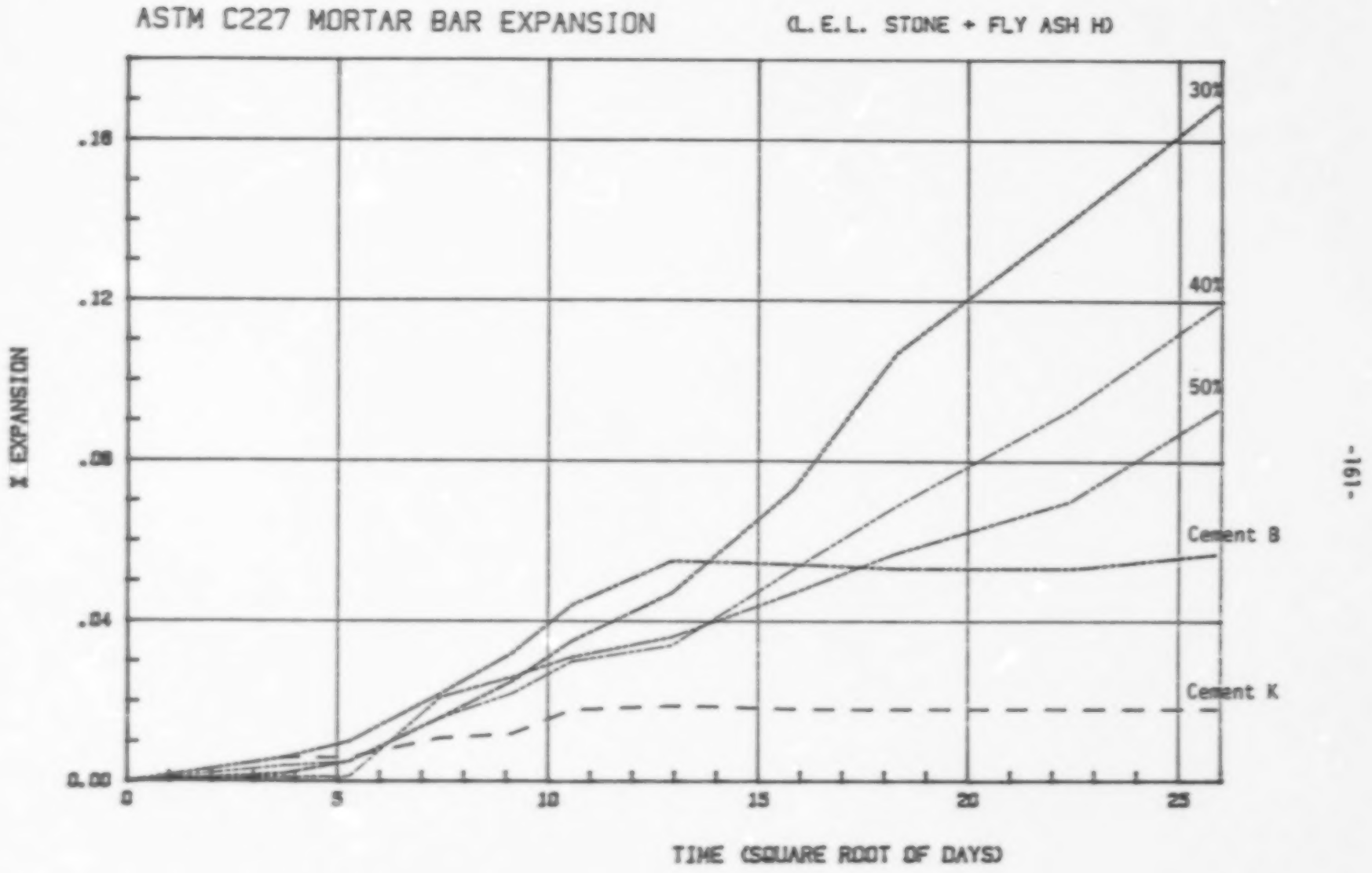

ASTM C227 MORTAR BAR EXPANSION
C.E.L. STONE + FLY ASH HD
% EXPANSION
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
30%
40%
50%
Cement B
Cement K

Figure 77

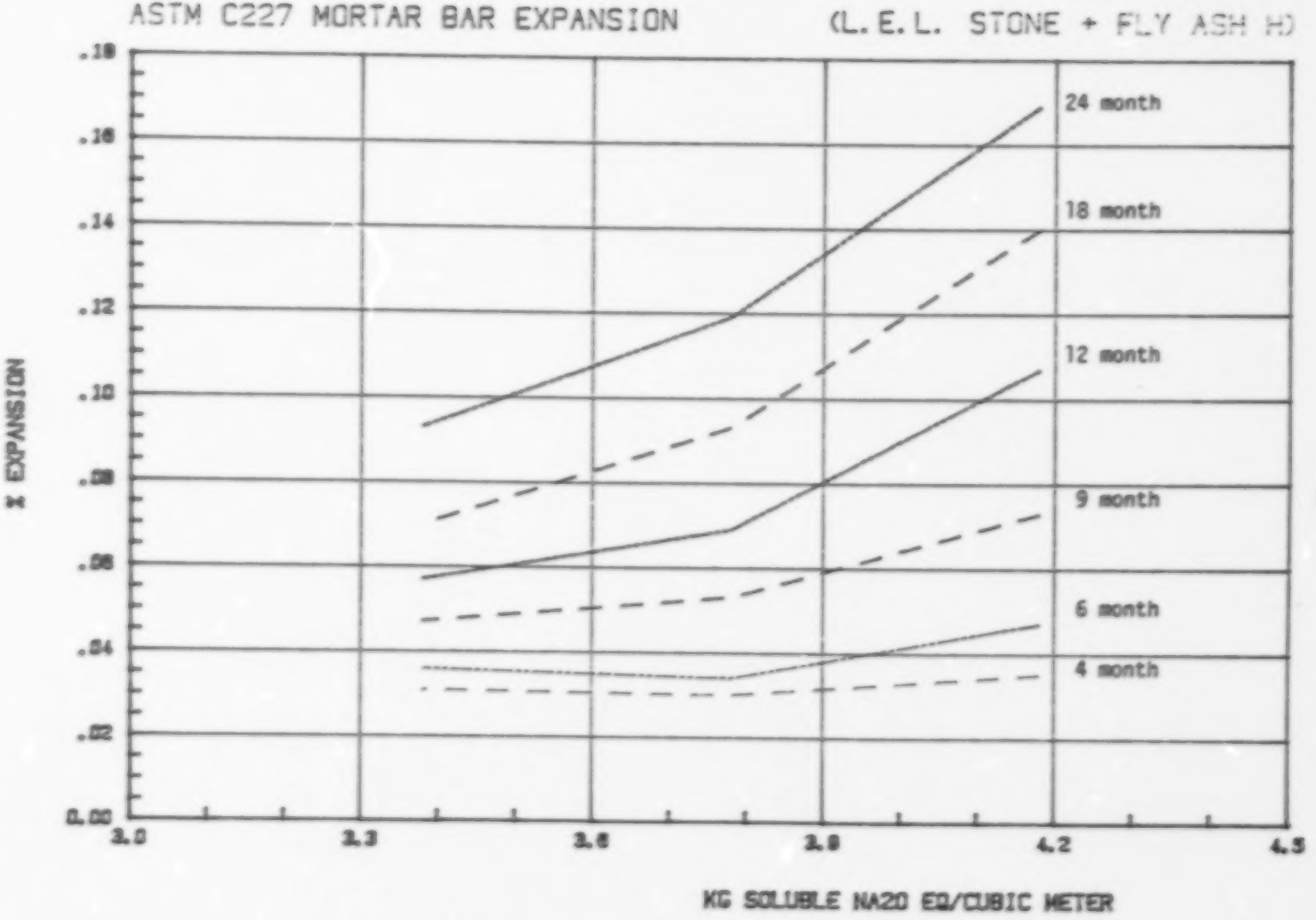

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + FLY ASH H)
% EXPANSION
.18
.16
.14
.12
.10
.08
.06
.04
.02
0.00
24 month
18 month
12 month
9 month
6 month
4 month
3.0
3.3
3.6
3.9
4.2
4.5
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 78

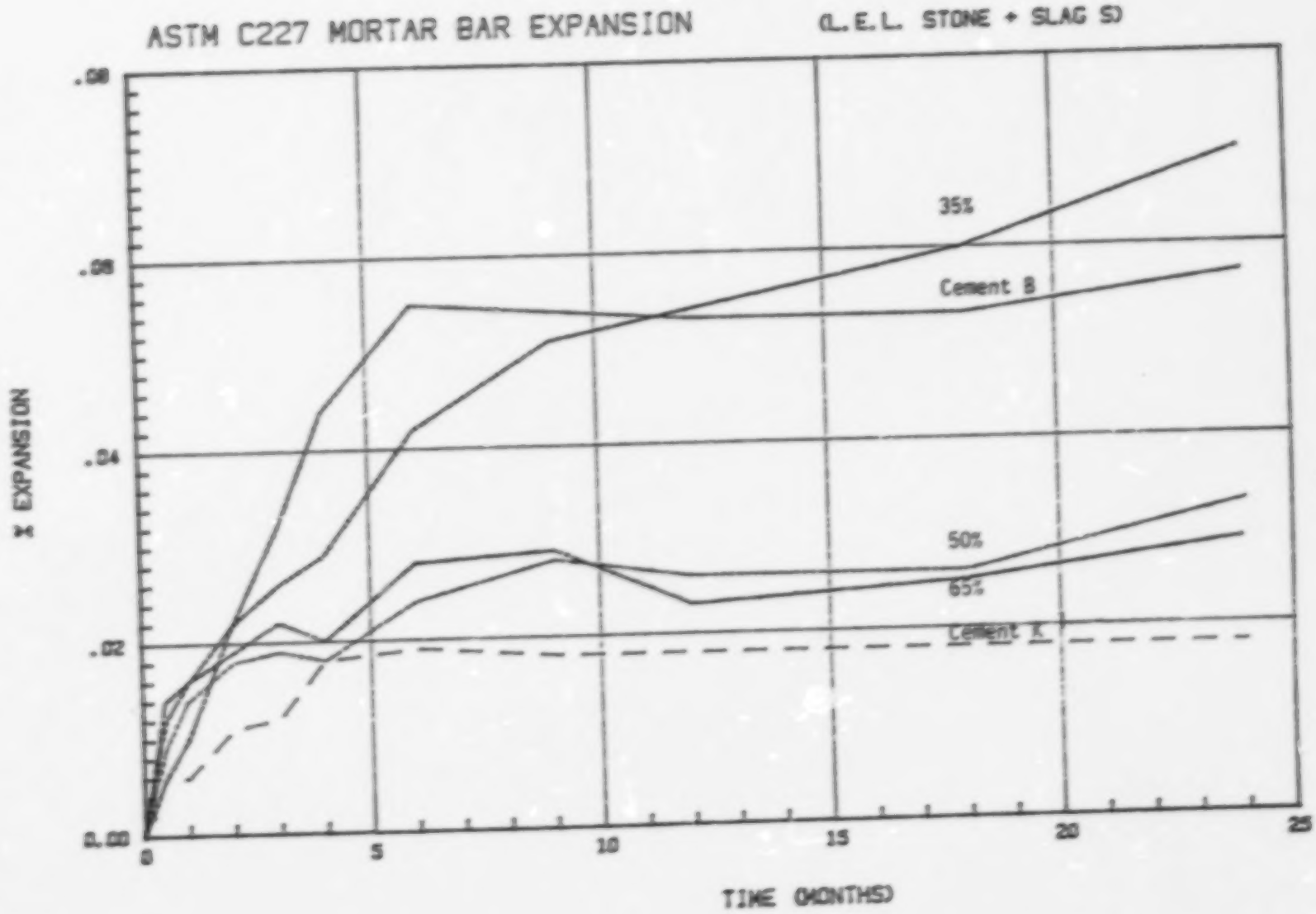

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG S)
% EXPANSION
.08
.06
.04
.02
0.00
0
5
10
15
20
25
TIME (MONTHS)
35%
Cement B
50%
65%
Cement K

Figure 79

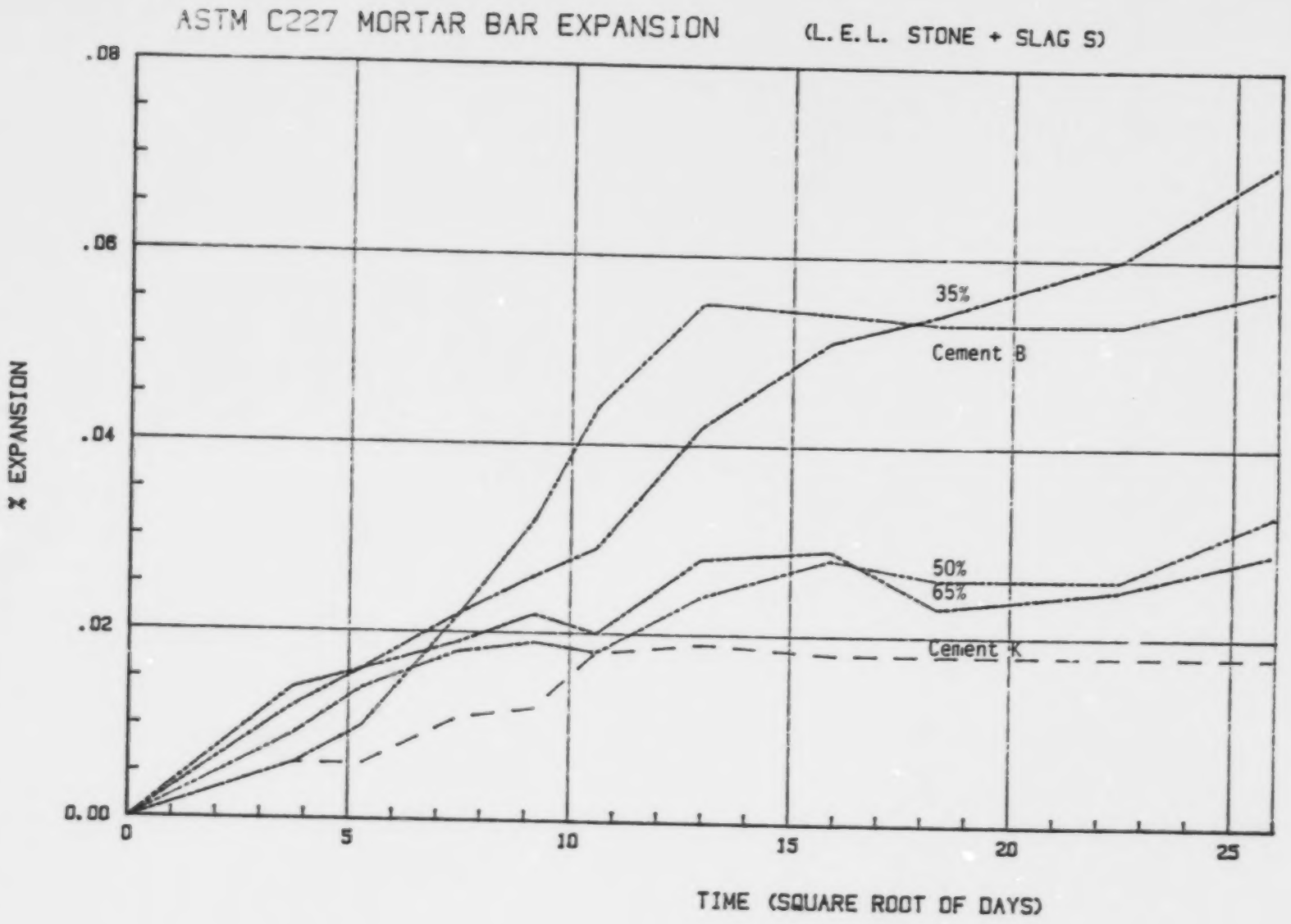

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG S)
.08
.06
.04
.02
0.00
% EXPANSION
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
35%
Cement B
50%
65%
Cement K

Figure 80

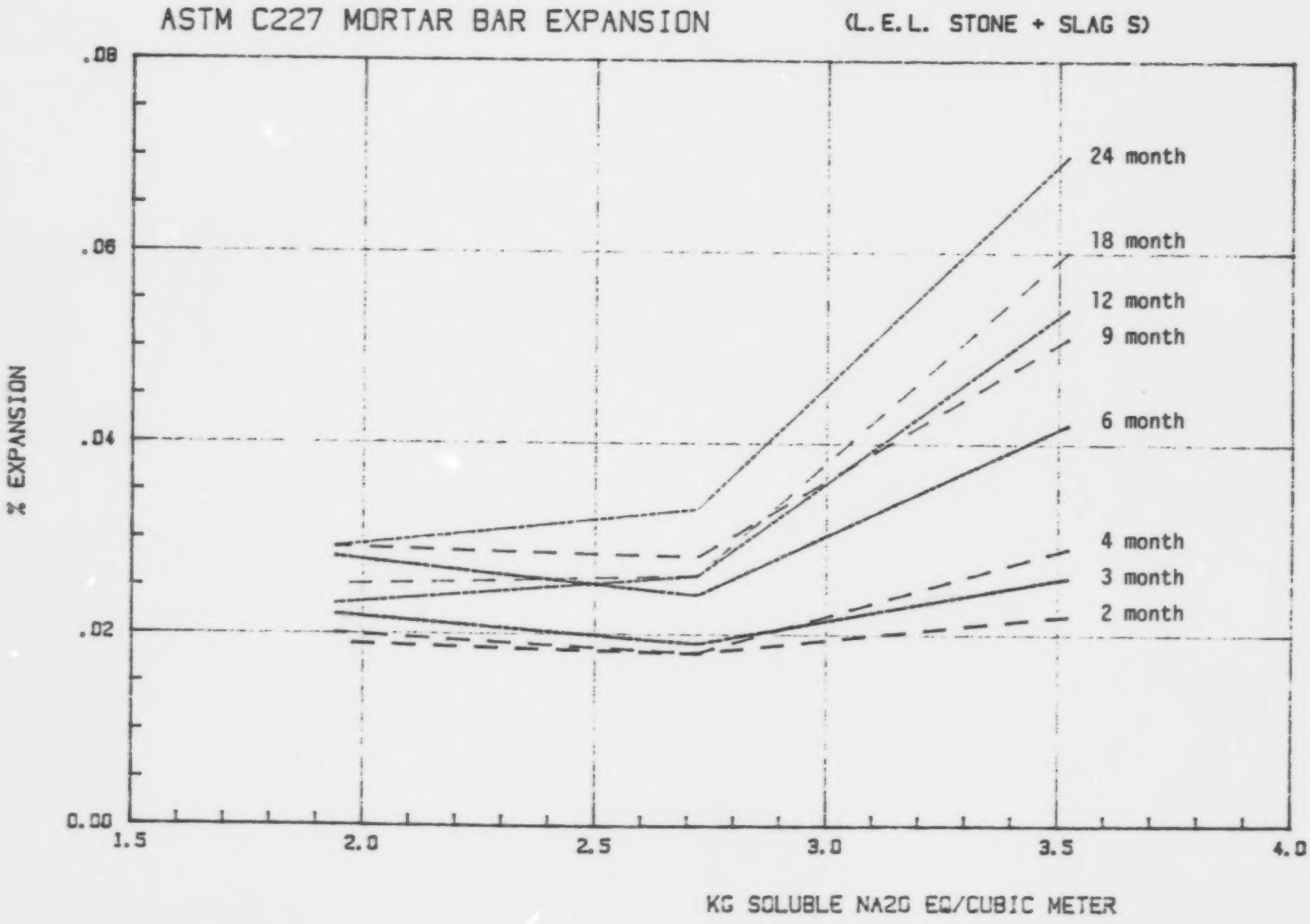

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG S)
.08
.06
.04
.02
0.00
% EXPANSION
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month
1.5
2.0
2.5
3.0
3.5
4.0
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 81

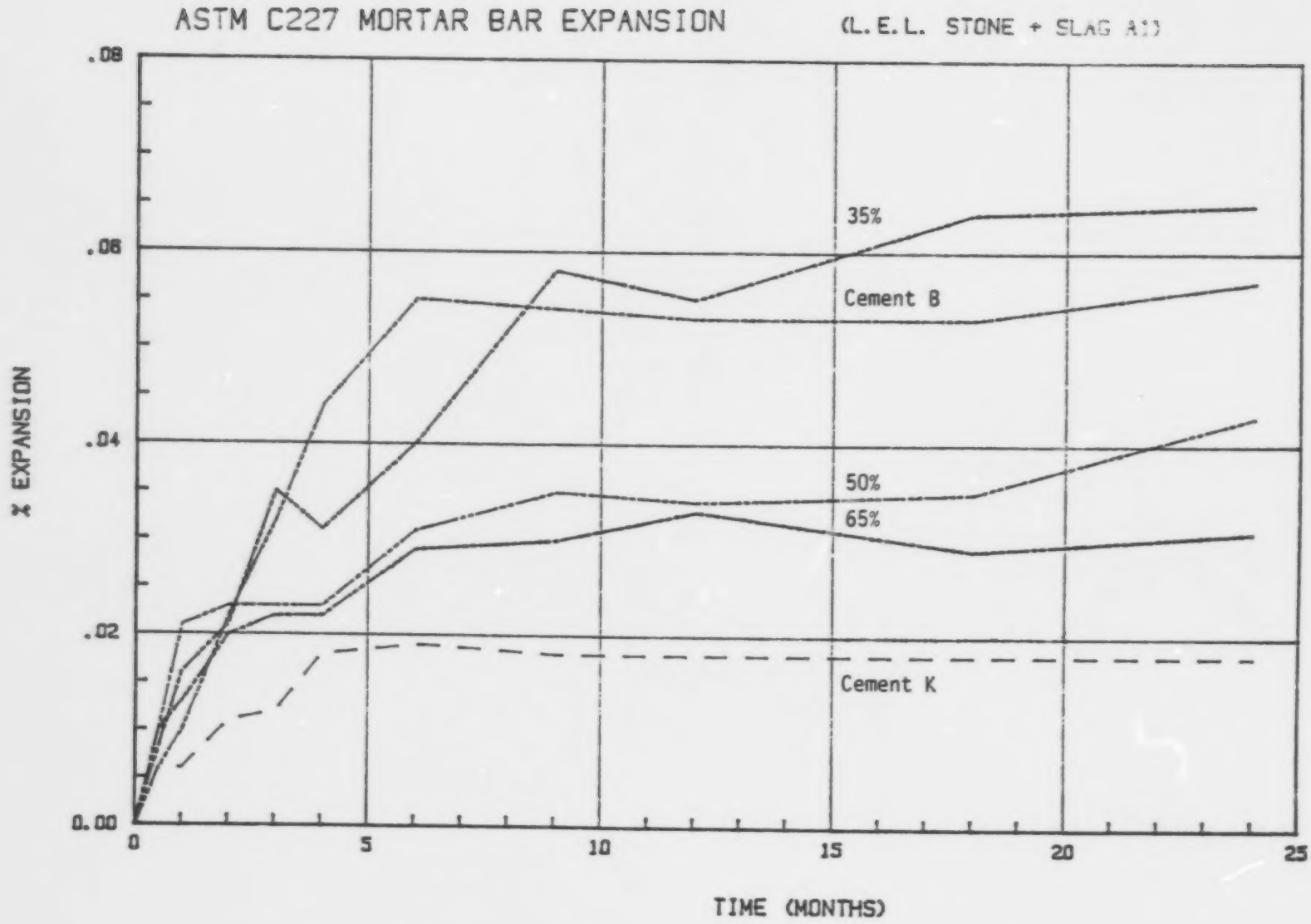

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG A)
.08
.06
.04
.02
0.00
% EXPANSION
0
5
10
15
20
25
TIME (MONTHS)
35%
Cement B
50%
65%
Cement K

Figure 82

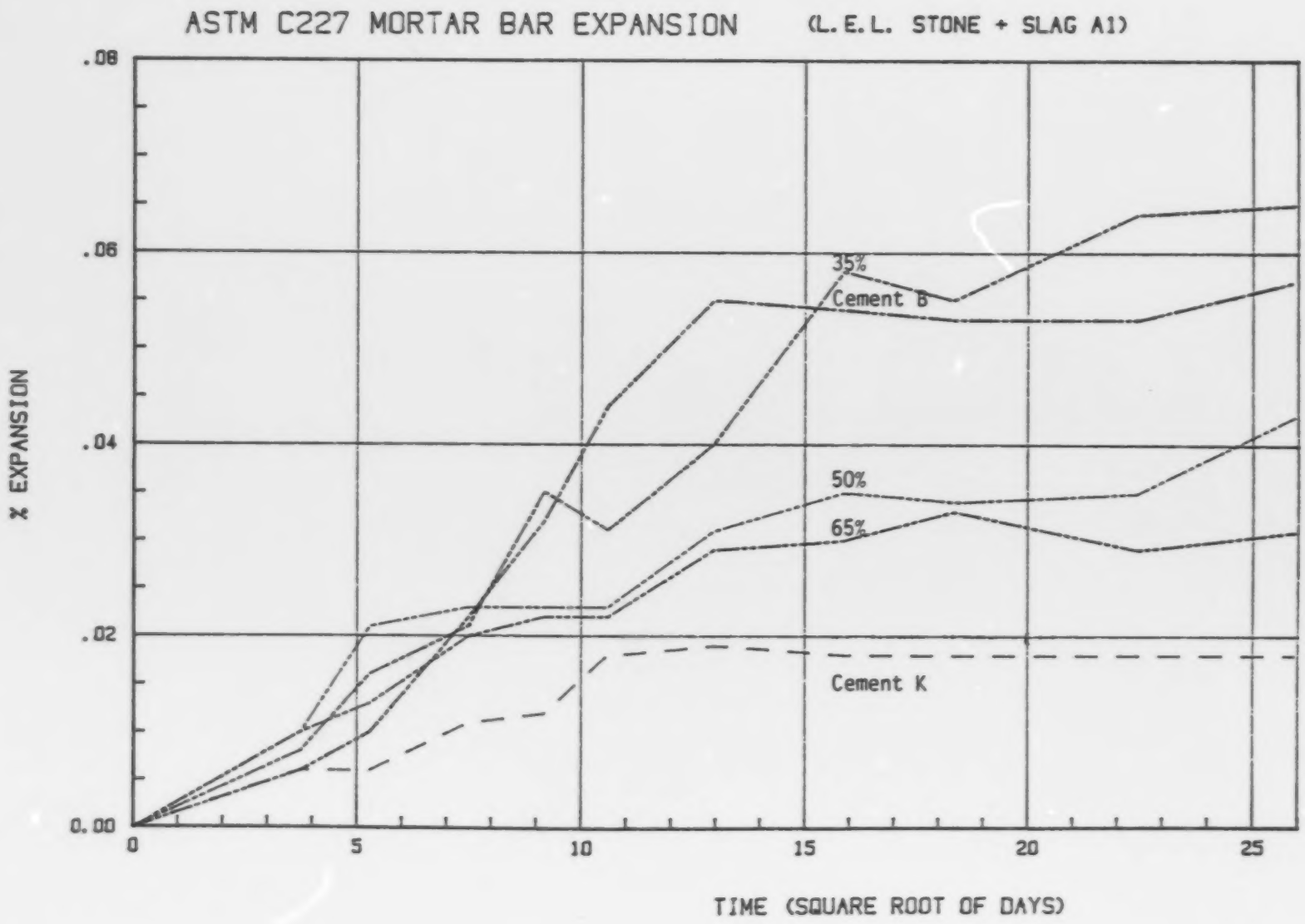

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG A1)
.08
.06
.04
.02
0.00
% EXPANSION
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
35%
Cement B
50%
65%
Cement K

Figure 83

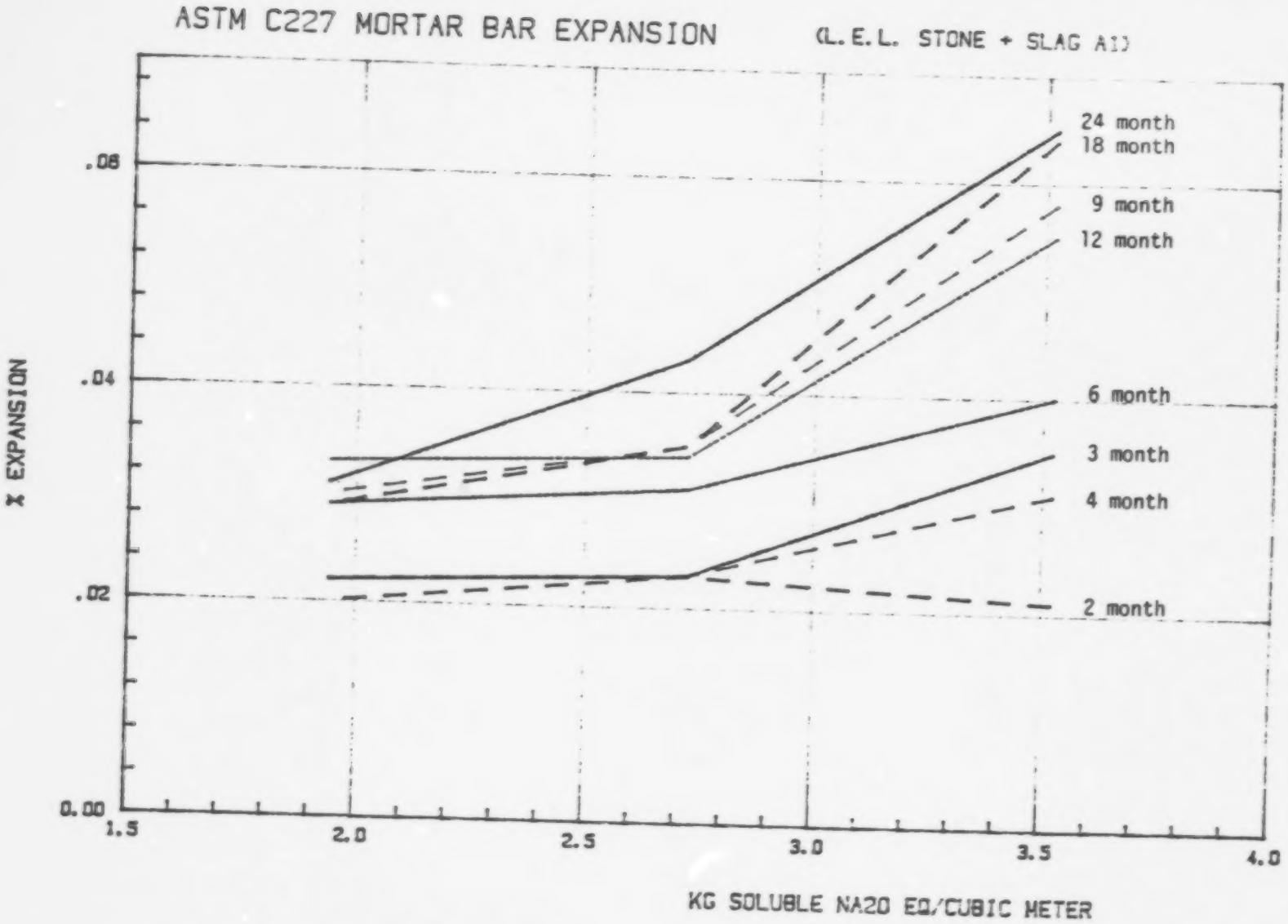

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG AI)
24 month
18 month
9 month
12 month
6 month
3 month
4 month
2 month
.08
.04
.02
0.00
% EXPANSION
1.5
2.0
2.5
3.0
3.5
4.0
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 84

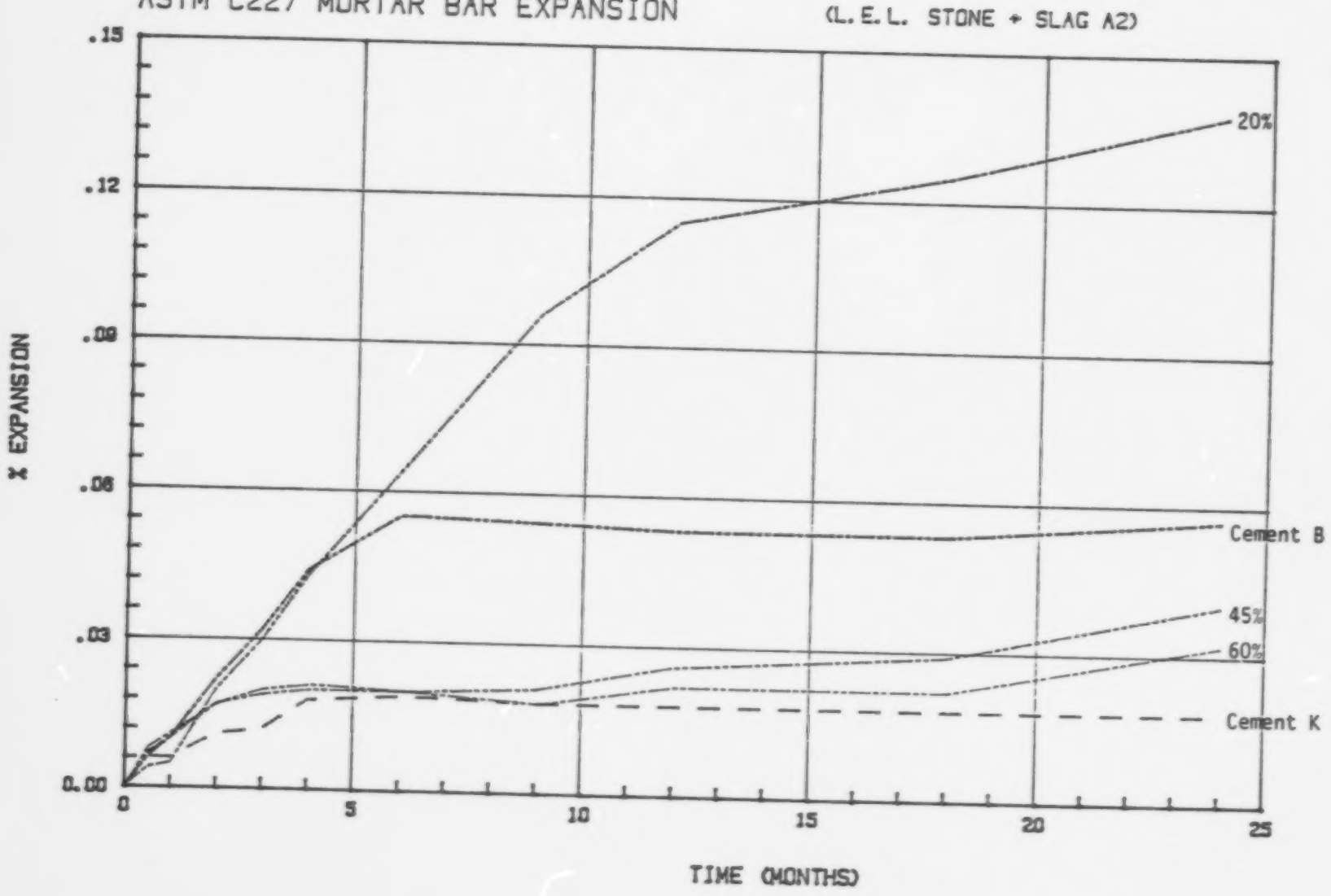

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG A2)
.15
.12
.09
.06
.03
0.00
% EXPANSION
0
5
10
15
20
25
TIME (MONTHS)
20%
Cement B
45%
60%
Cement K

Figure 85

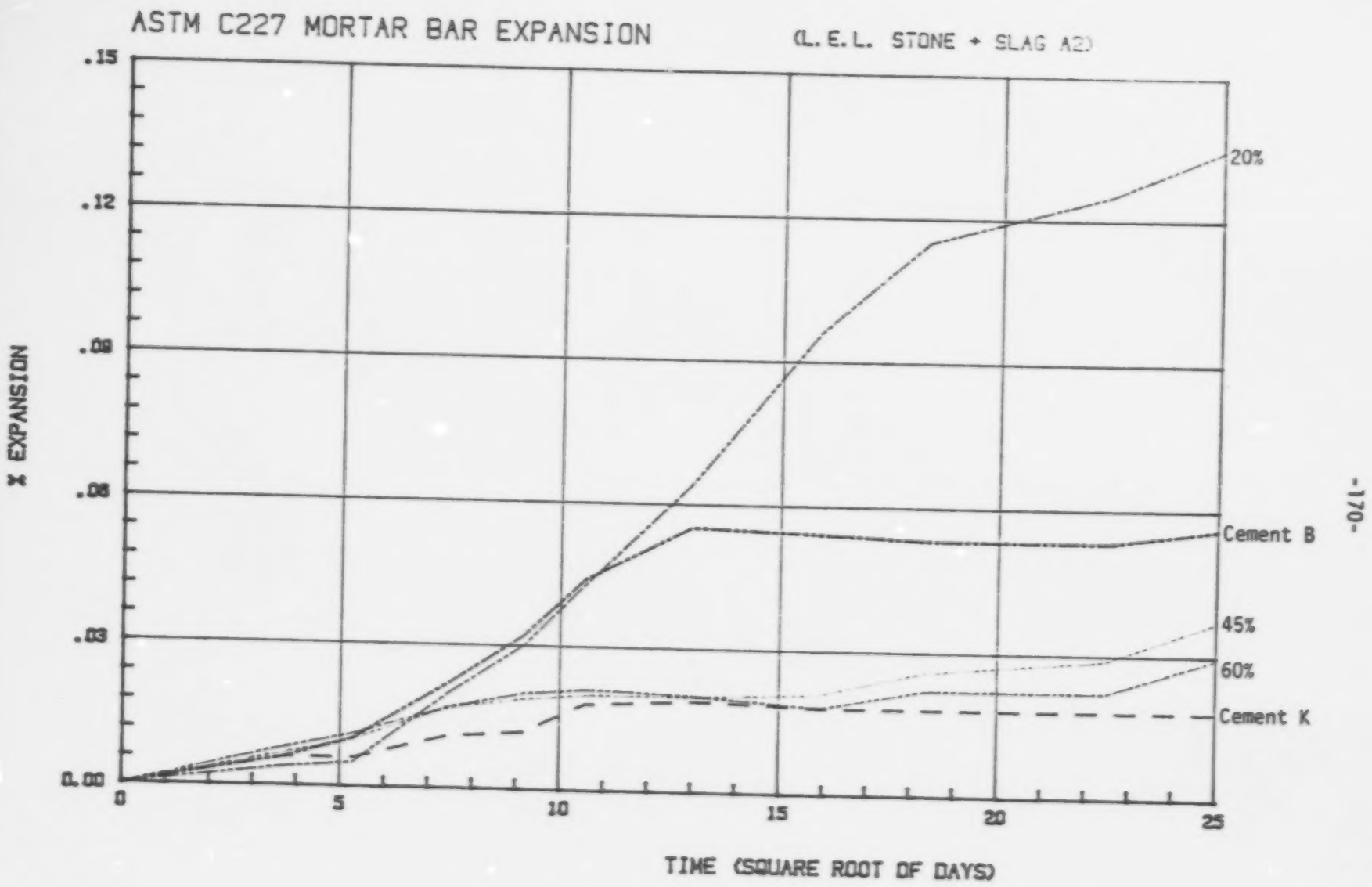

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG A2)
.15
.12
.09
.06
.03
0.00
% EXPANSION
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
20%
Cement B
45%
60%
Cement K

Figure 86

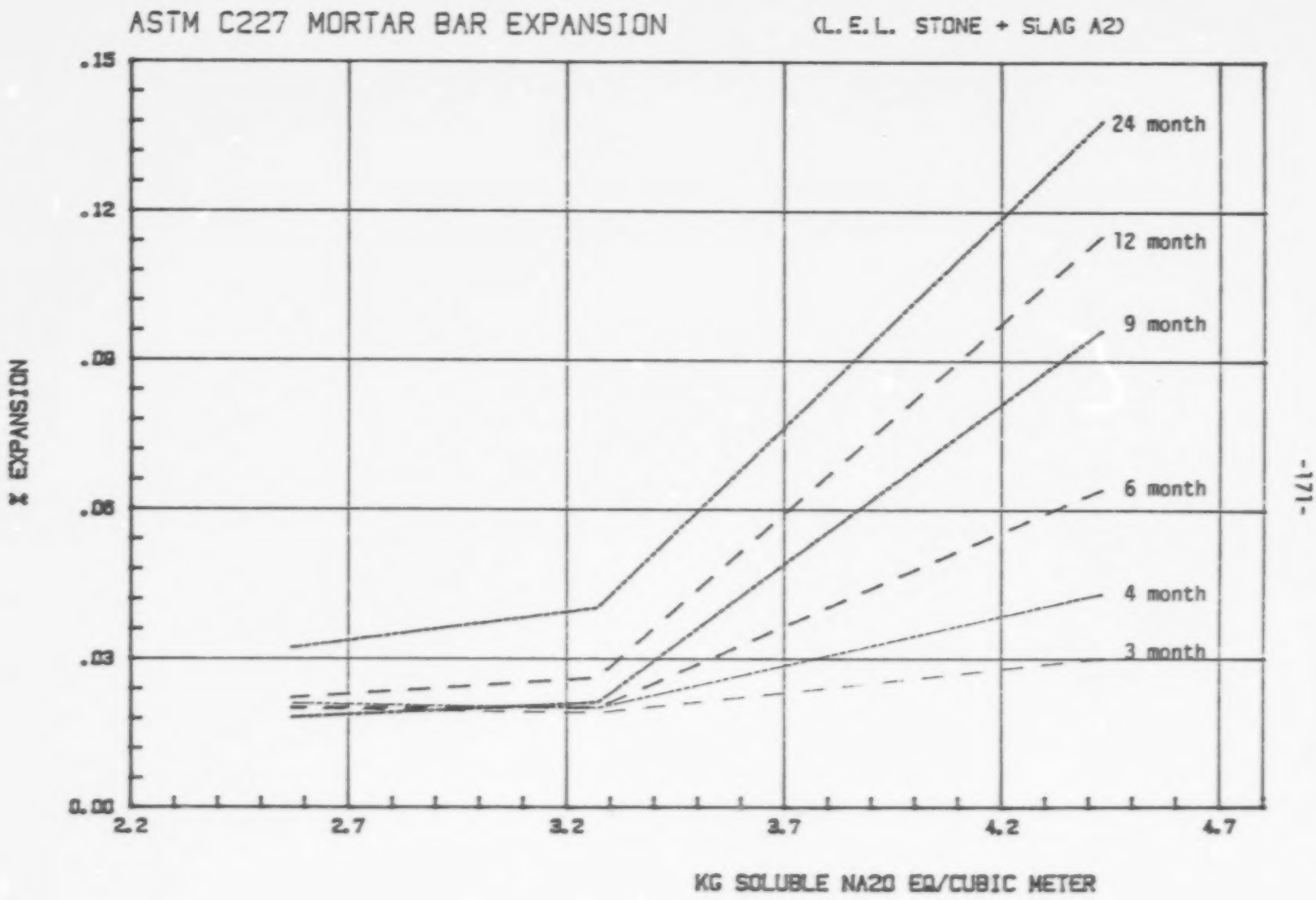

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + SLAG A2)
% EXPANSION
.15
.12
.09
.06
.03
0.00
2.2
2.7
3.2
3.7
4.2
4.7
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
12 month
9 month
6 month
4 month
3 month

Figure 87

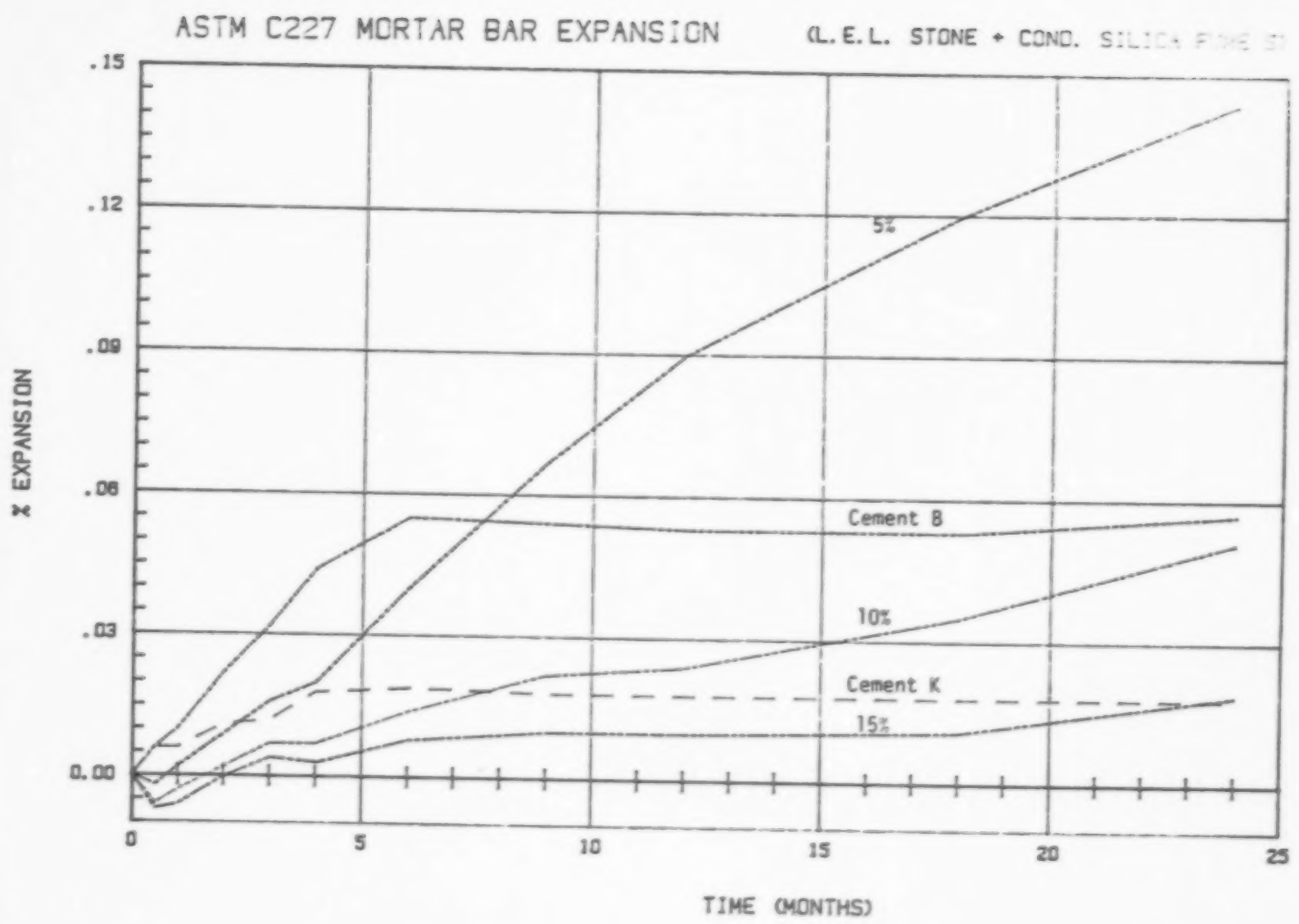

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + COND. SILICA FUME S)
.15
.12
.09
.06
.03
0.00
% EXPANSION
5%
Cement B
10%
Cement K
15%
0
5
10
15
20
25
TIME (MONTHS)

Figure 88

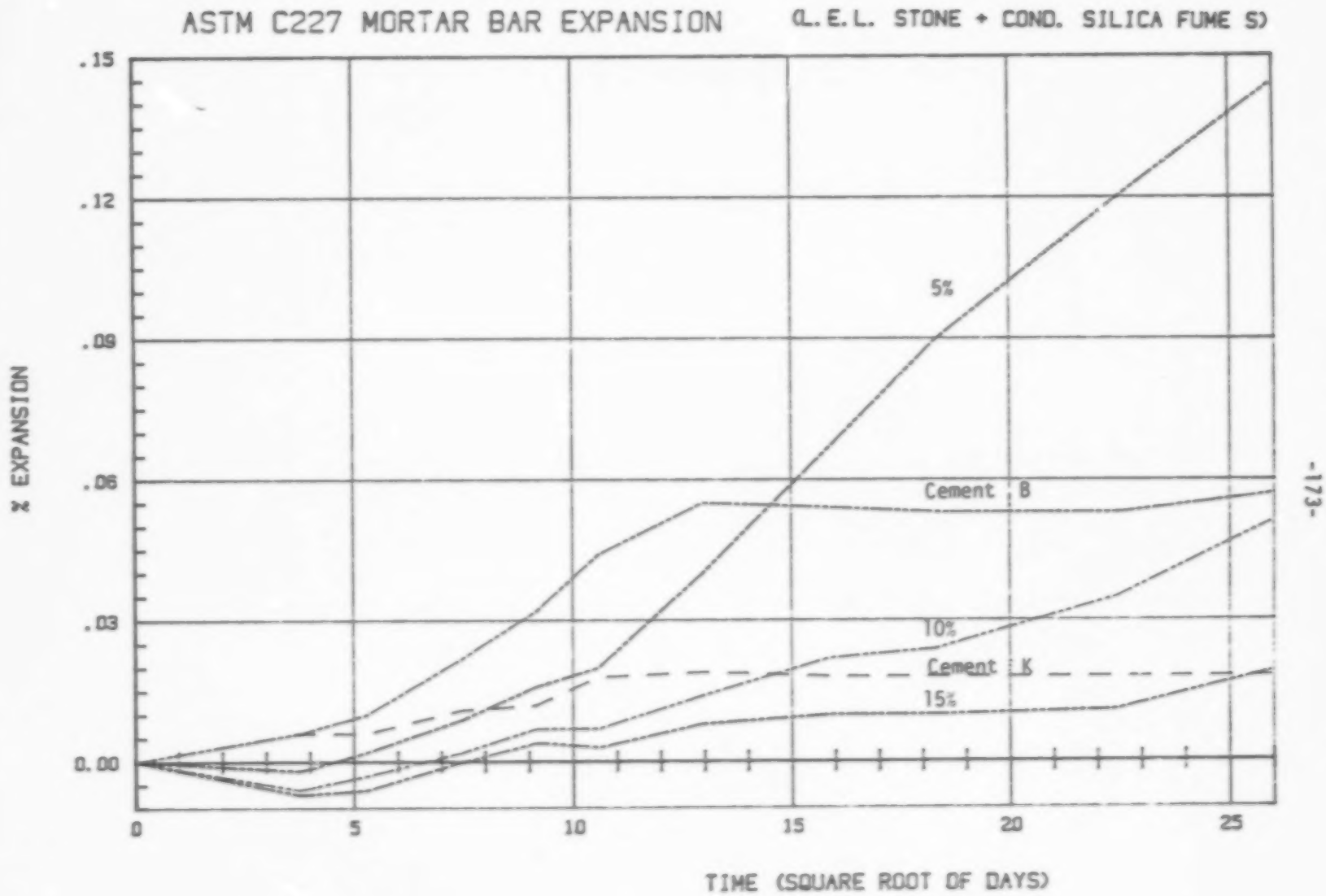

ASTM C227 MORTAR BAR EXPANSION
Q.E.L. STONE + COND. SILICA FUME S)
.15
.12
.09
.06
.03
0.00
% EXPANSION
5%
Cement B
10%
Cement K
15%
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)

Figure 89

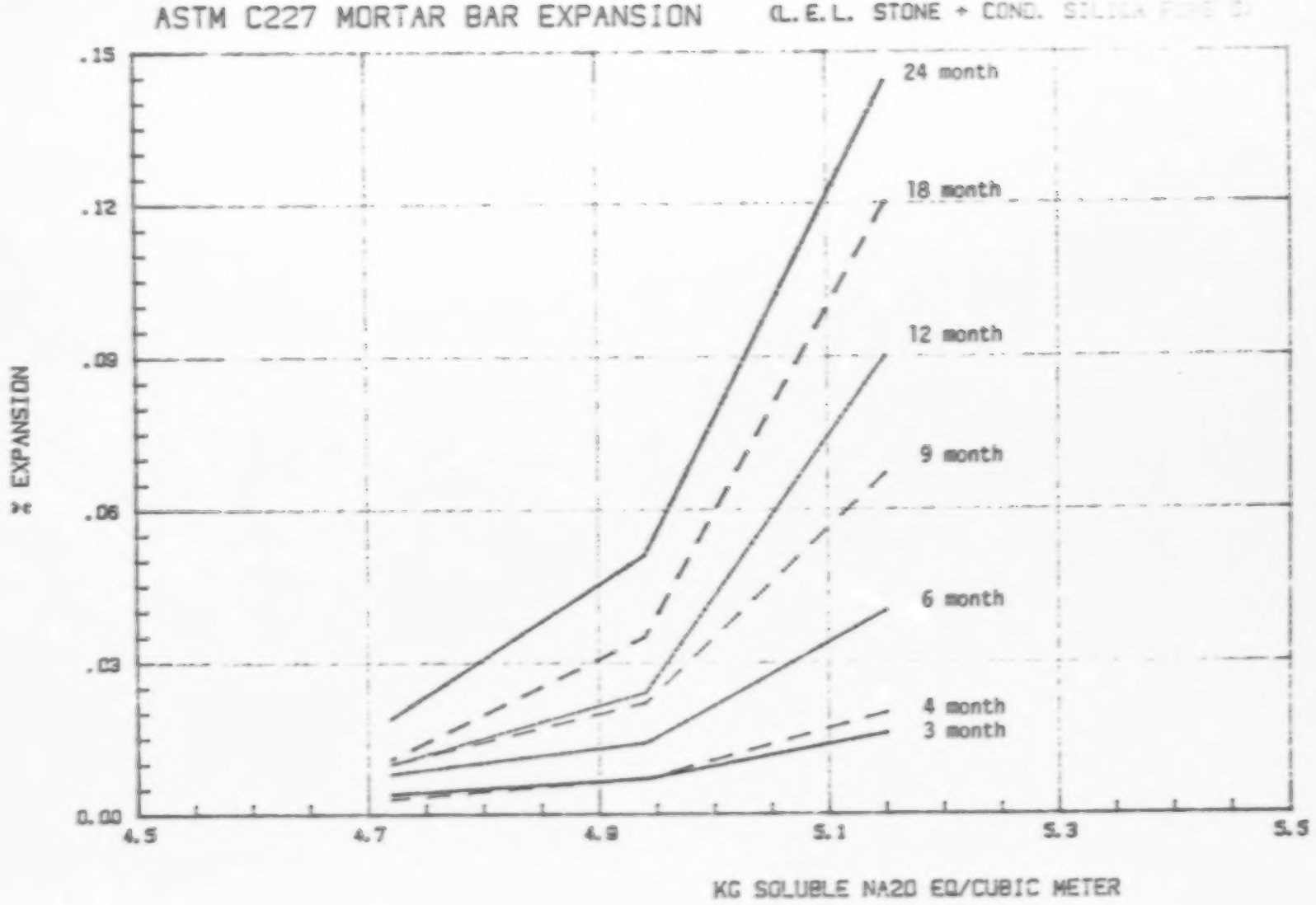

ASTM C227 MORTAR BAR EXPANSION
.15
.12
.09
.06
.03
0.00
% EXPANSION
24 month
18 month
12 month
9 month
6 month
4 month
3 month
4.5
4.7
4.9
5.1
5.3
5.5
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 90

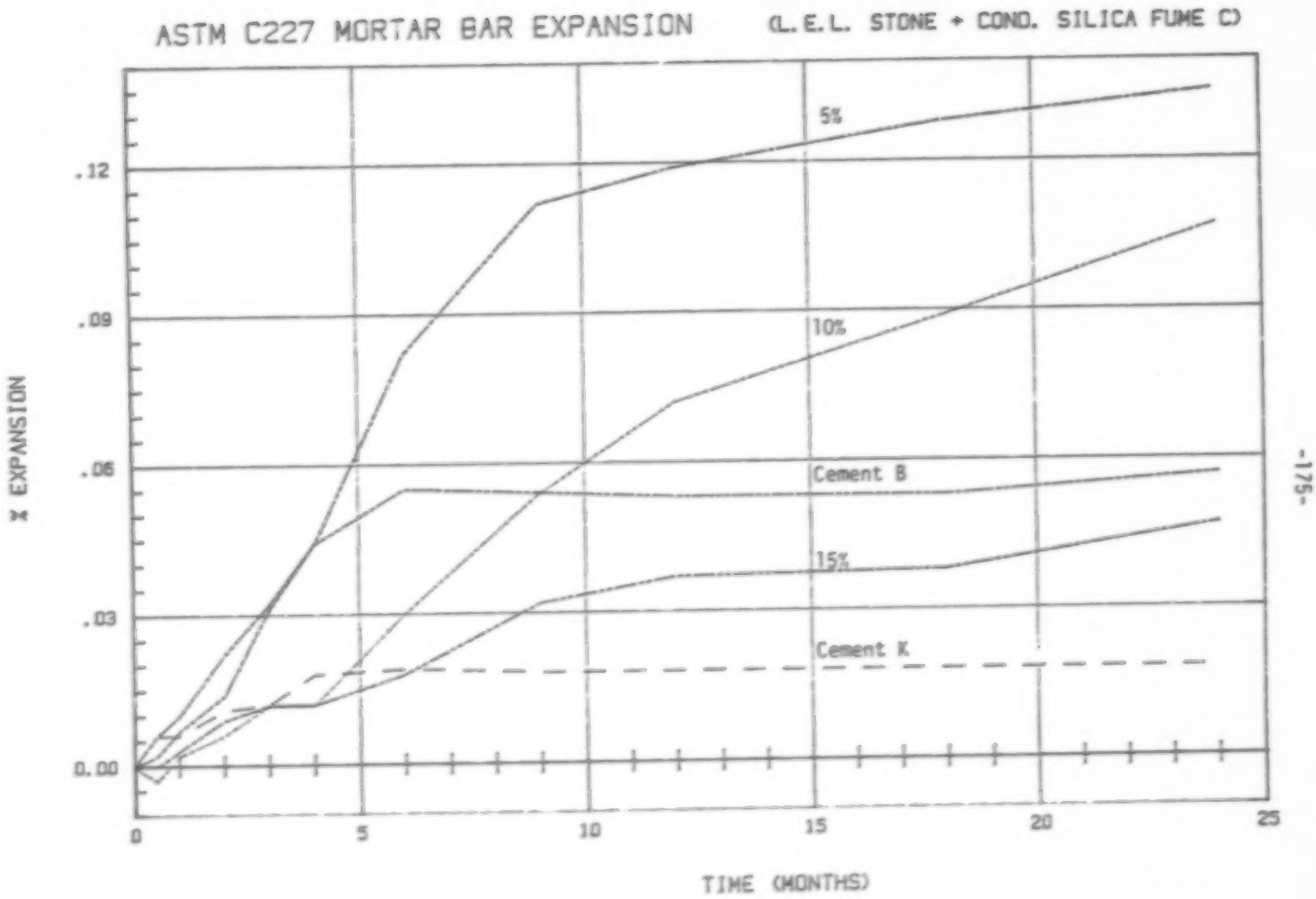

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + COND. SILICA FUME C)
% EXPANSION
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
5%
10%
Cement B
15%
Cement K

Figure 91

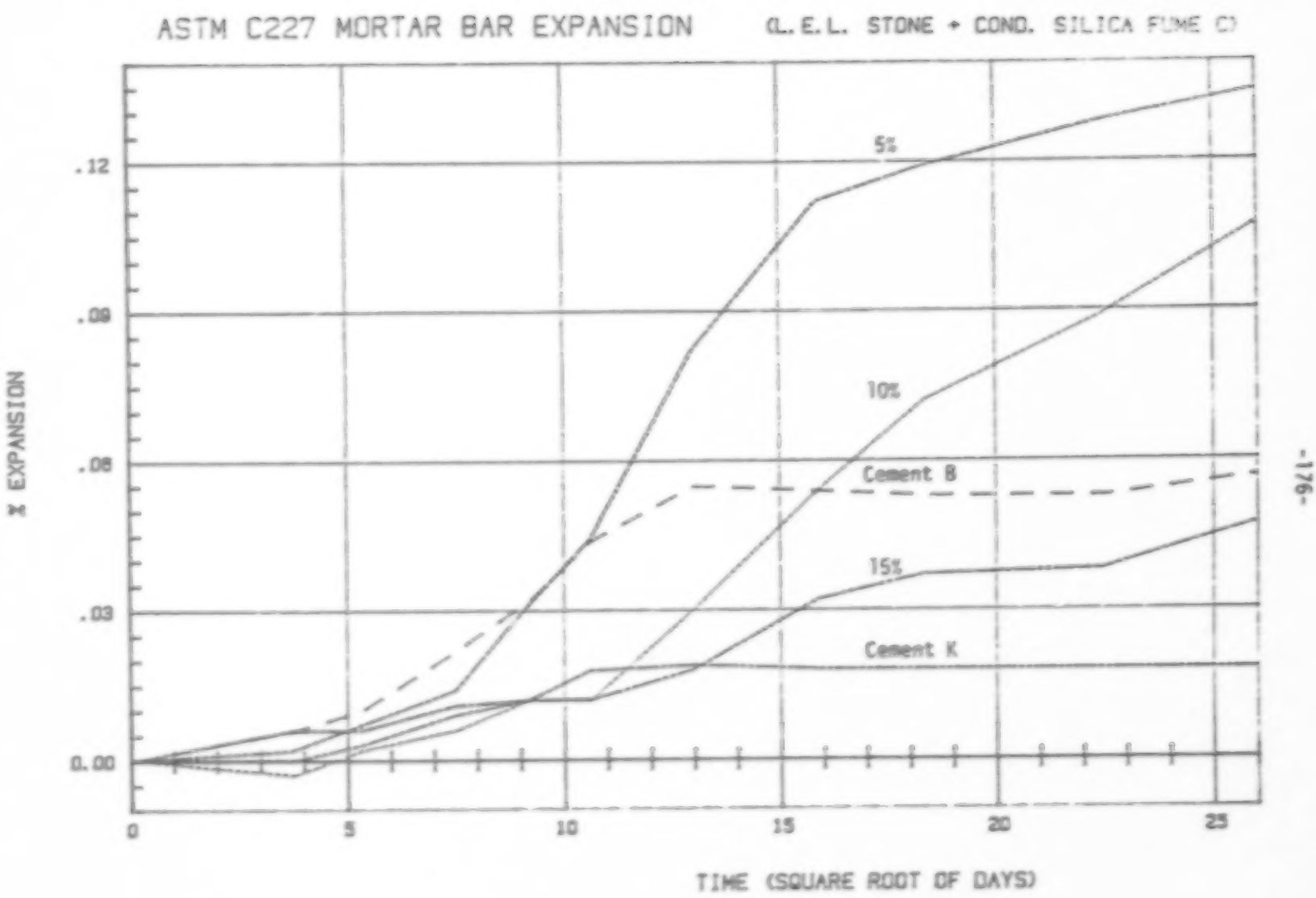

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + COND. SILICA FUME C)
% EXPANSION
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
5%
10%
15%
Cement B
Cement K

Figure 92

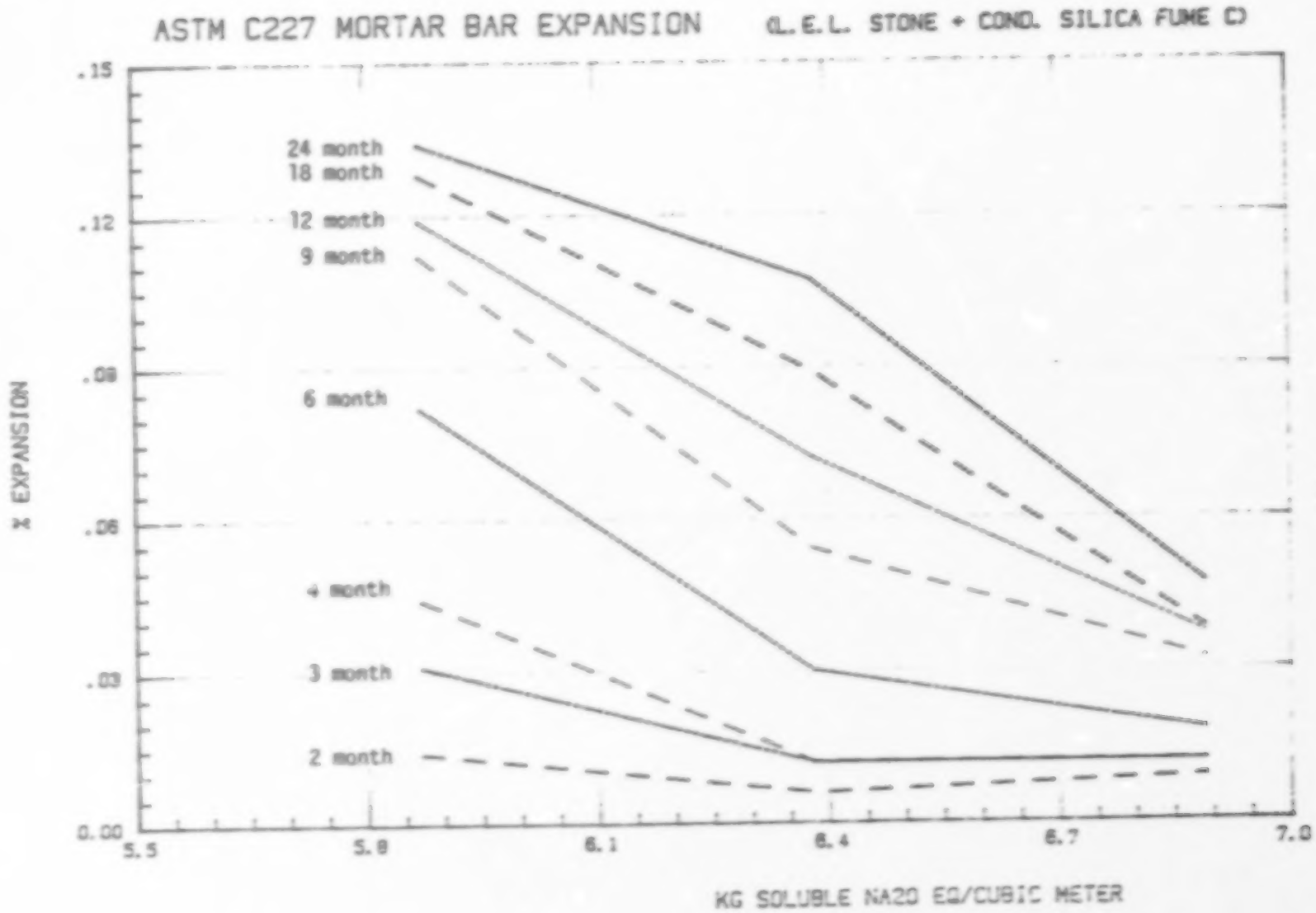

ASTM C227 MORTAR BAR EXPANSION
G.E.L. STONE + COND. SILICA FUME C)
% EXPANSION
.15
.12
.09
.06
.03
0.00
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month
5.5
5.8
6.1
6.4
6.7
7.0
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 93

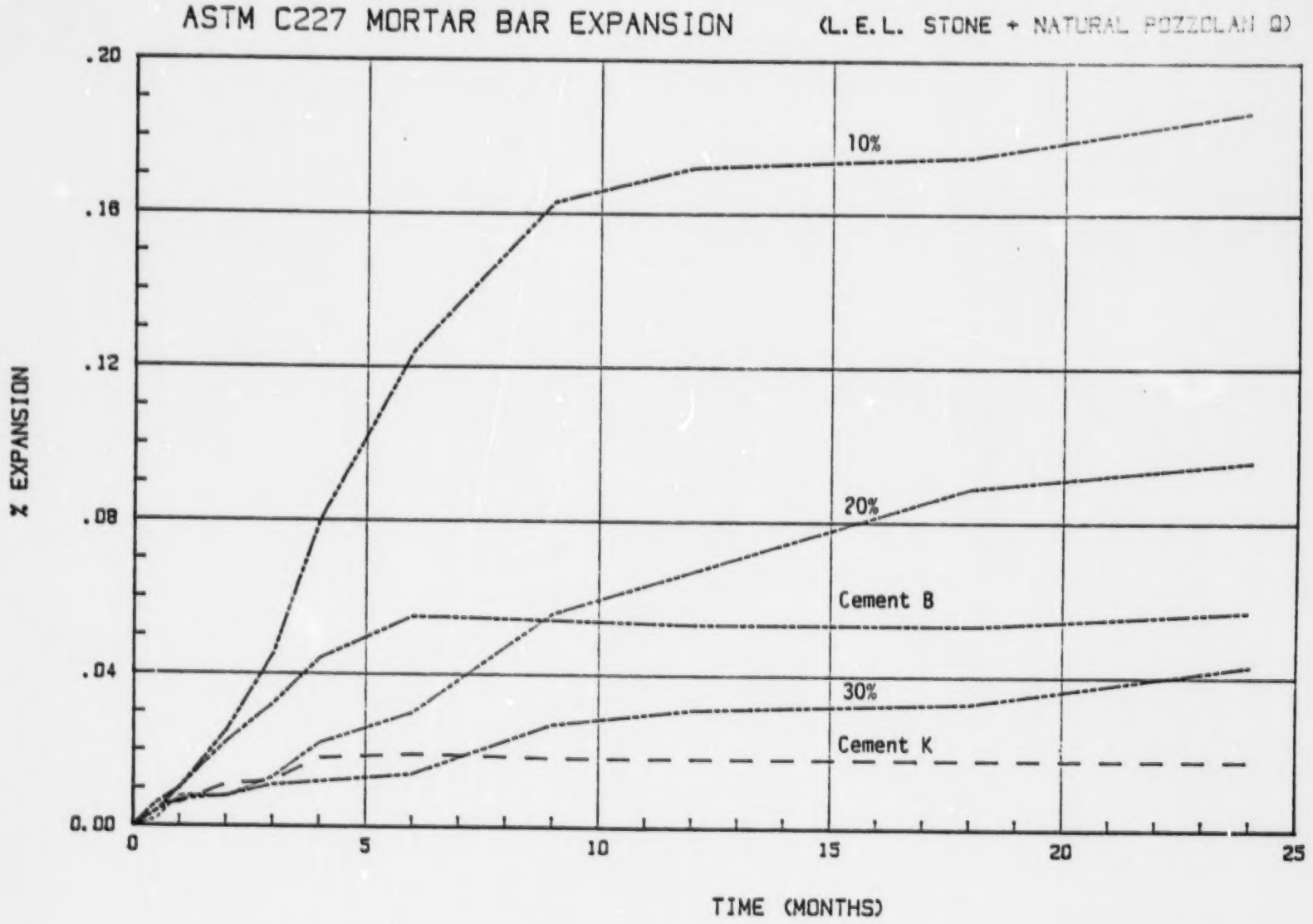

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + NATURAL POZZOLAN @)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (MONTHS)
10%
20%
30%
Cement B
Cement K

Figure 94

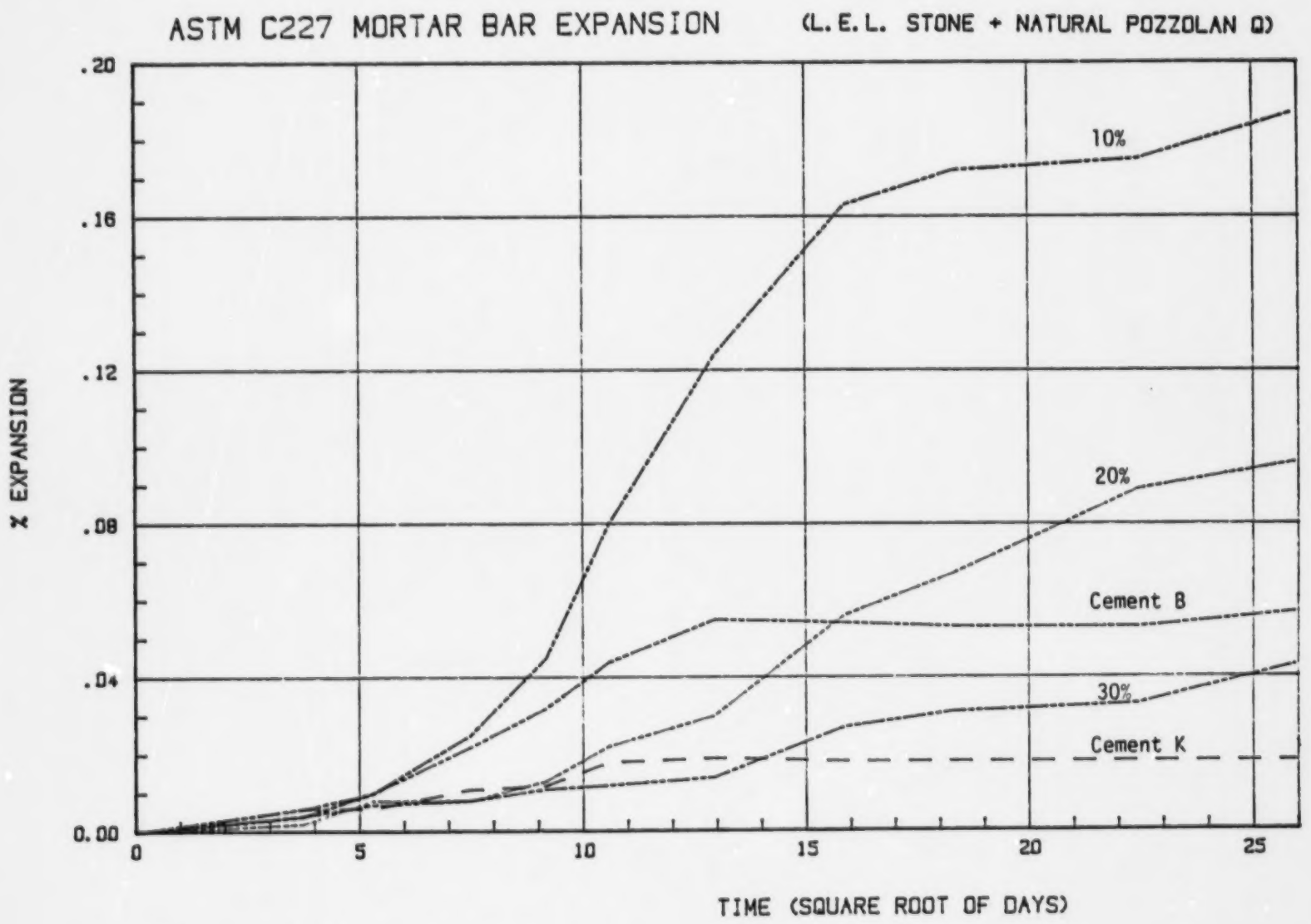

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + NATURAL POZZOLAN Q)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
20%
Cement B
30%
Cement K

Figure 95

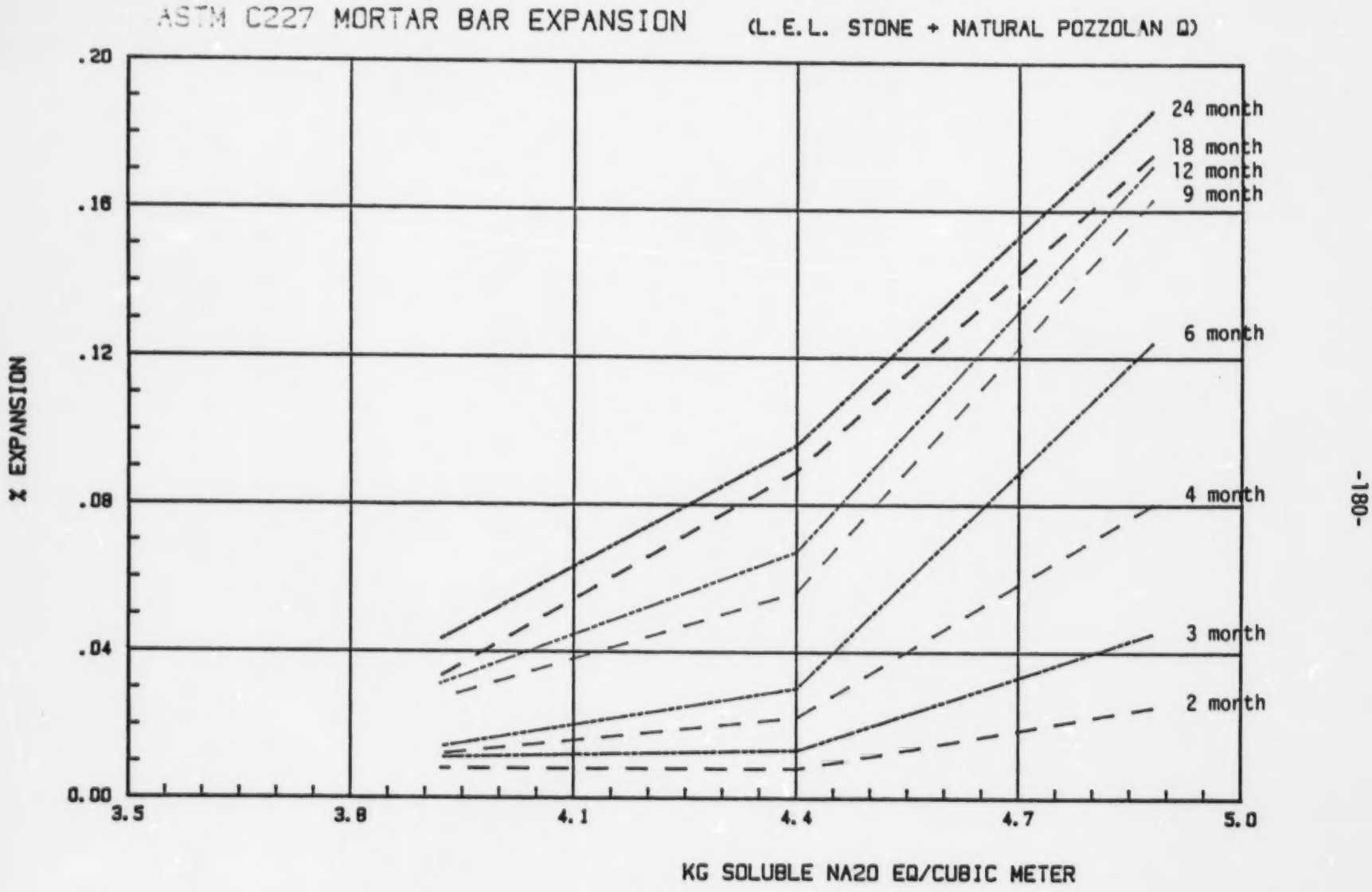

ASTM C227 MORTAR BAR EXPANSION
(L.E.L. STONE + NATURAL POZZOLAN Q)
% EXPANSION
.20
.16
.12
.08
.04
0.00
3.5
3.8
4.1
4.4
4.7
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 96

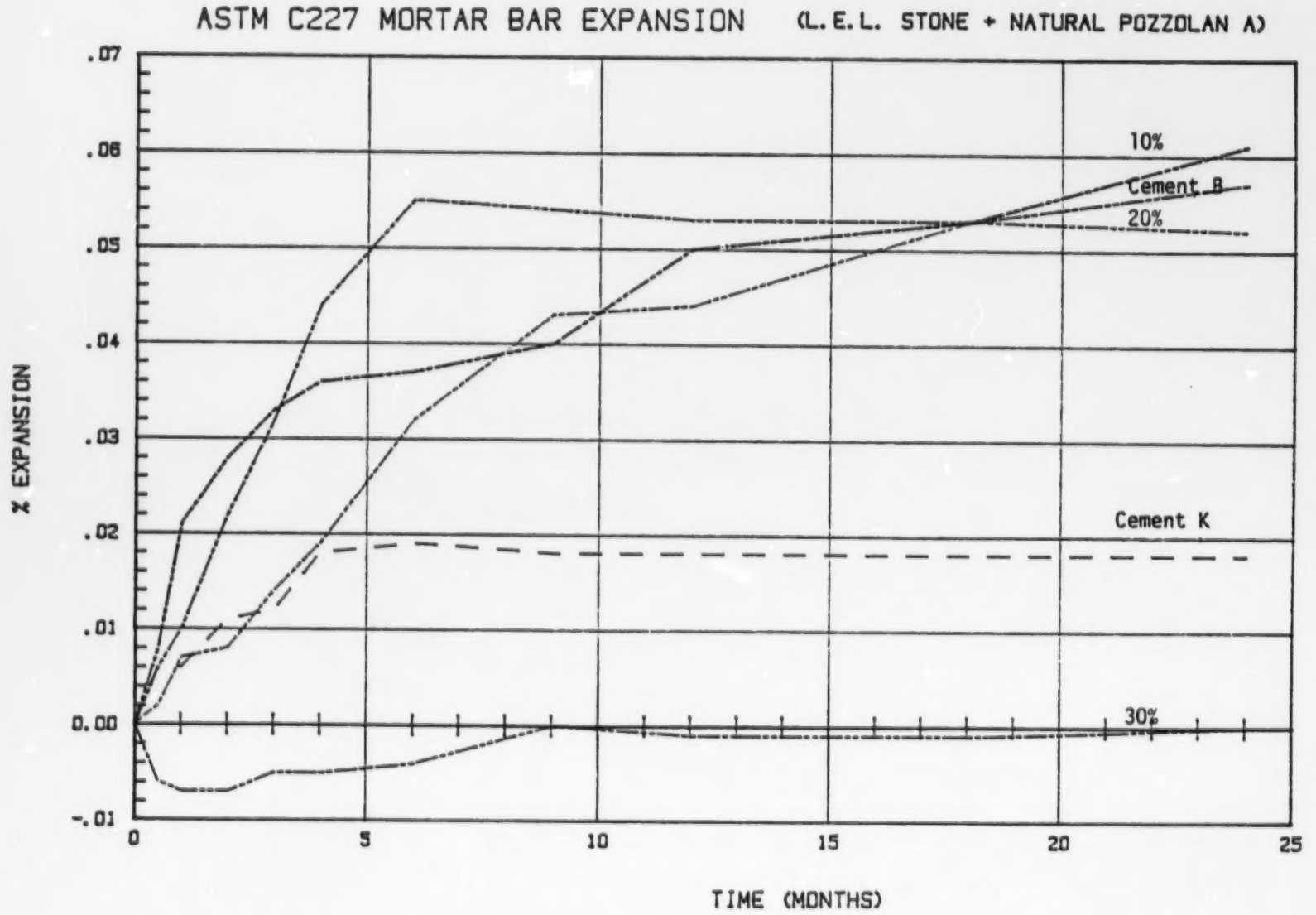

ASTM C227 MORTAR BAR EXPANSION (L.E.L. STONE + NATURAL POZZOLAN A)
% EXPANSION
.07
.06
.05
.04
.03
.02
.01
0.00
-.01
0
5
10
15
20
25
TIME (MONTHS)
10%
Cement B
20%
Cement K
30%

Figure 97

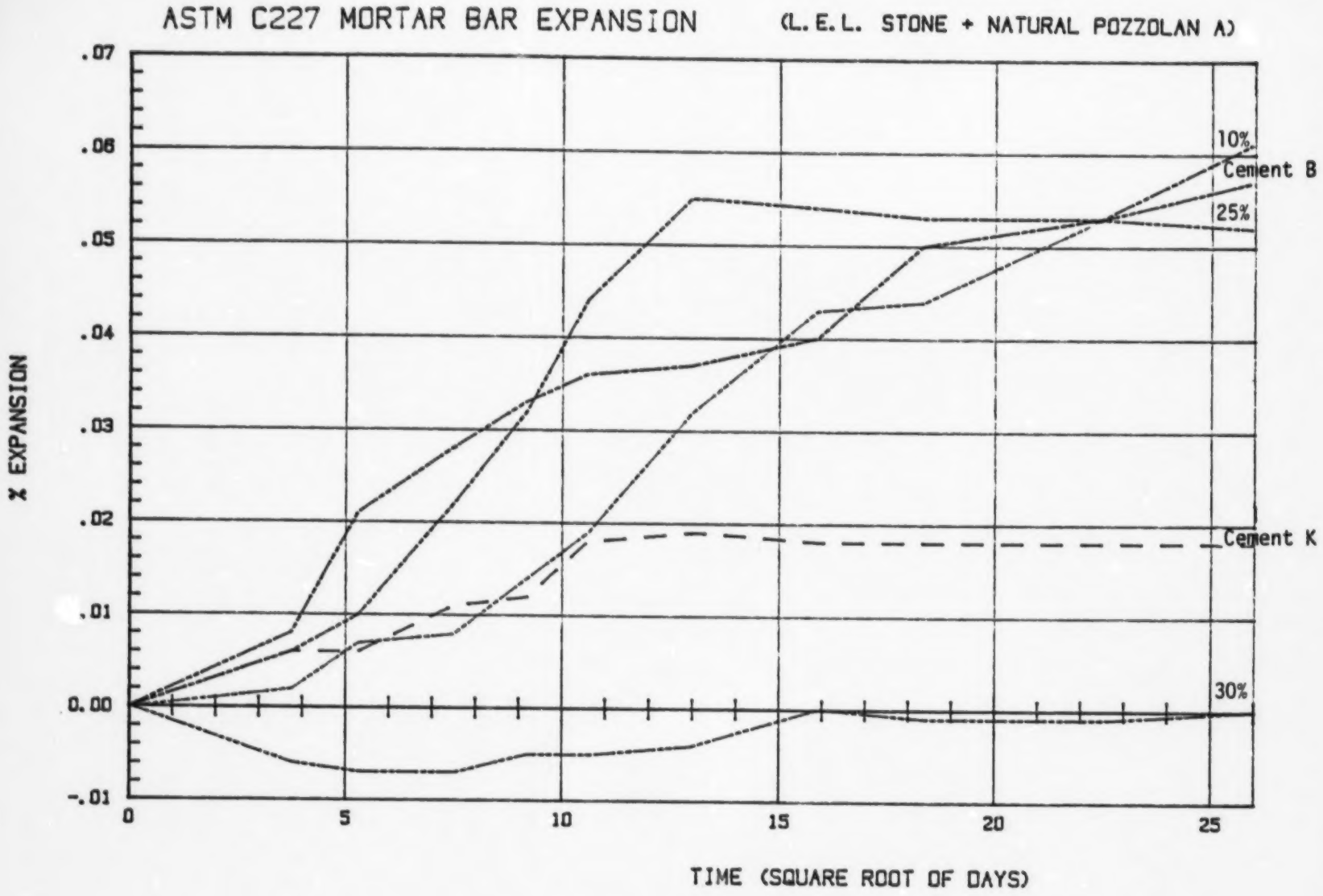

ASTM C227 MORTAR BAR EXPANSION
(L. E. L. STONE + NATURAL POZZOLAN A)
% EXPANSION
.07
.06
.05
.04
.03
.02
.01
0.00
-.01
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
10%
Cement B
25%
Cement K
30%

Figure 98

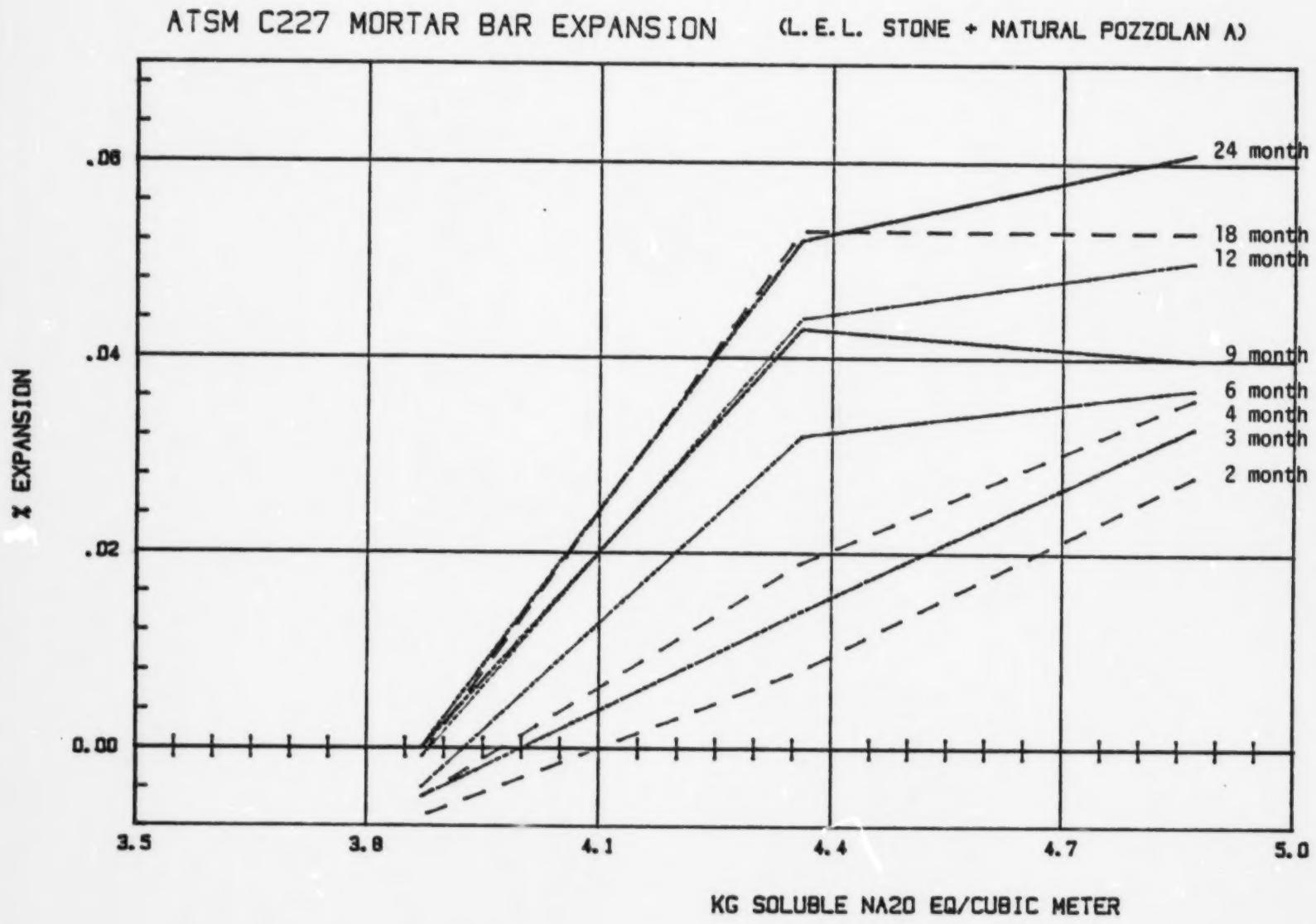

ATSM C227 MORTAR BAR EXPANSION (L. E. L. STONE + NATURAL POZZOLAN A)
% EXPANSION
.06
.04
.02
0.00
3.5
3.8
4.1
4.4
4.7
5.0
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
9 month
6 month
4 month
3 month
2 month

Figure 99

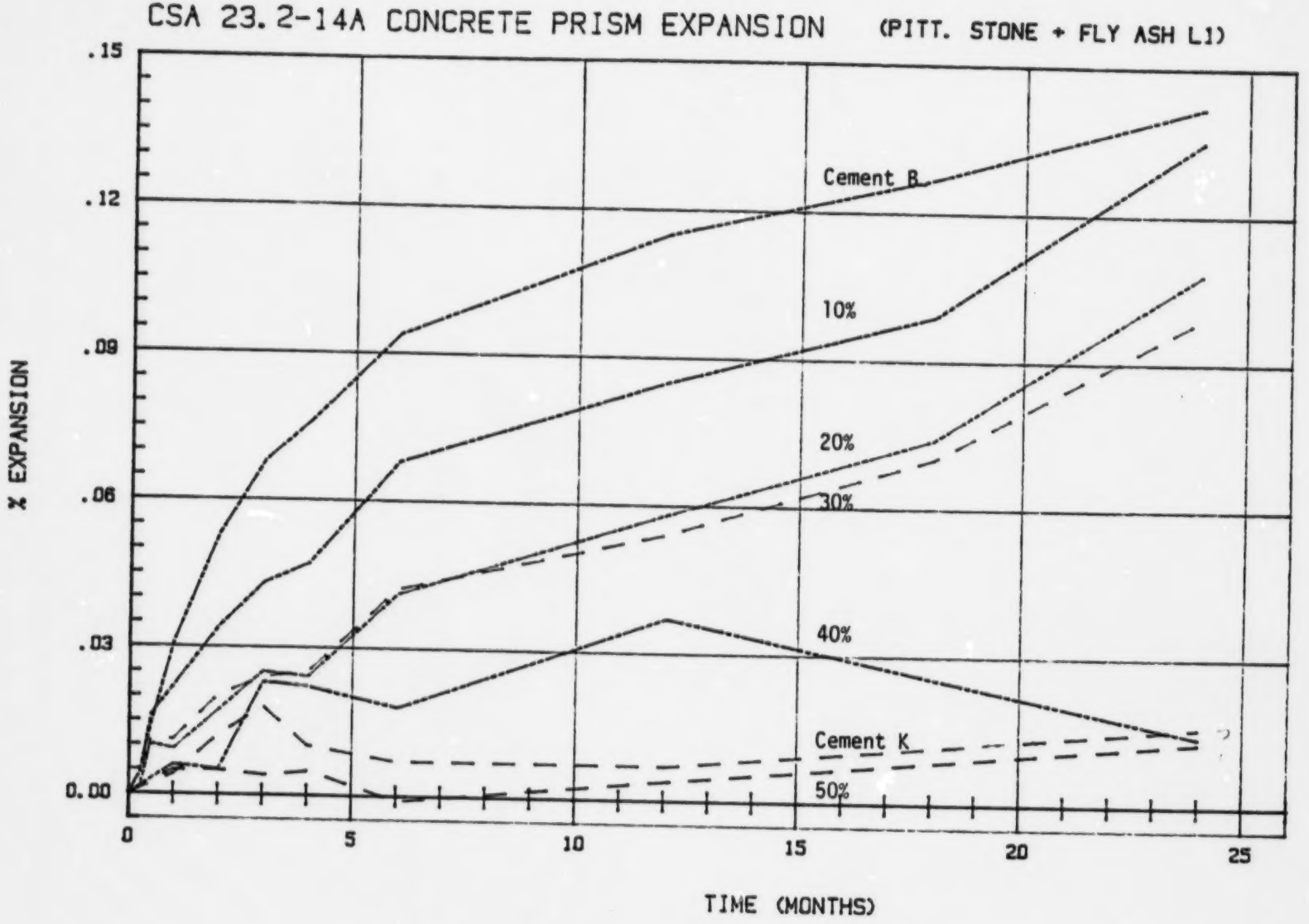

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L1)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 100

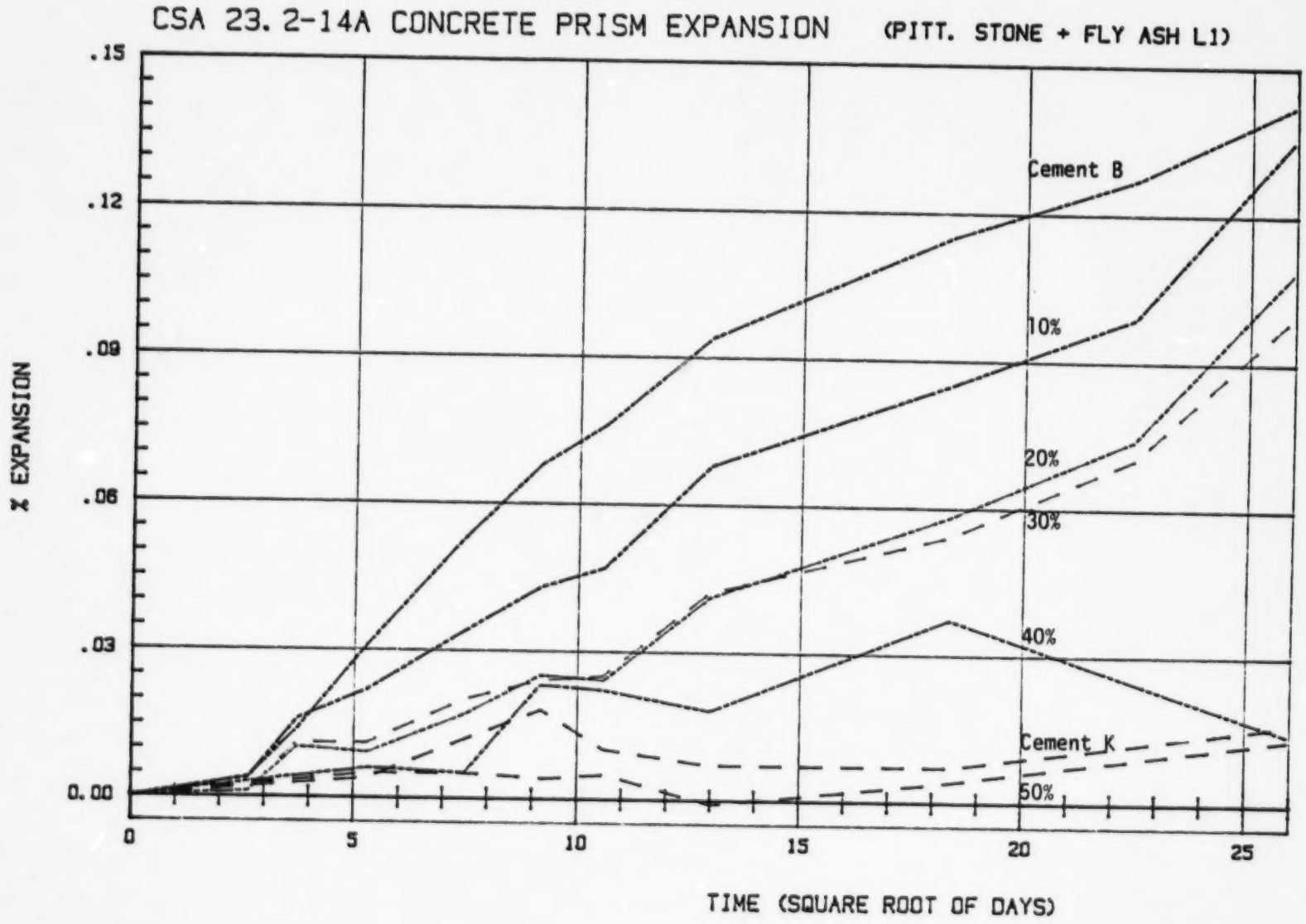

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L1)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 101

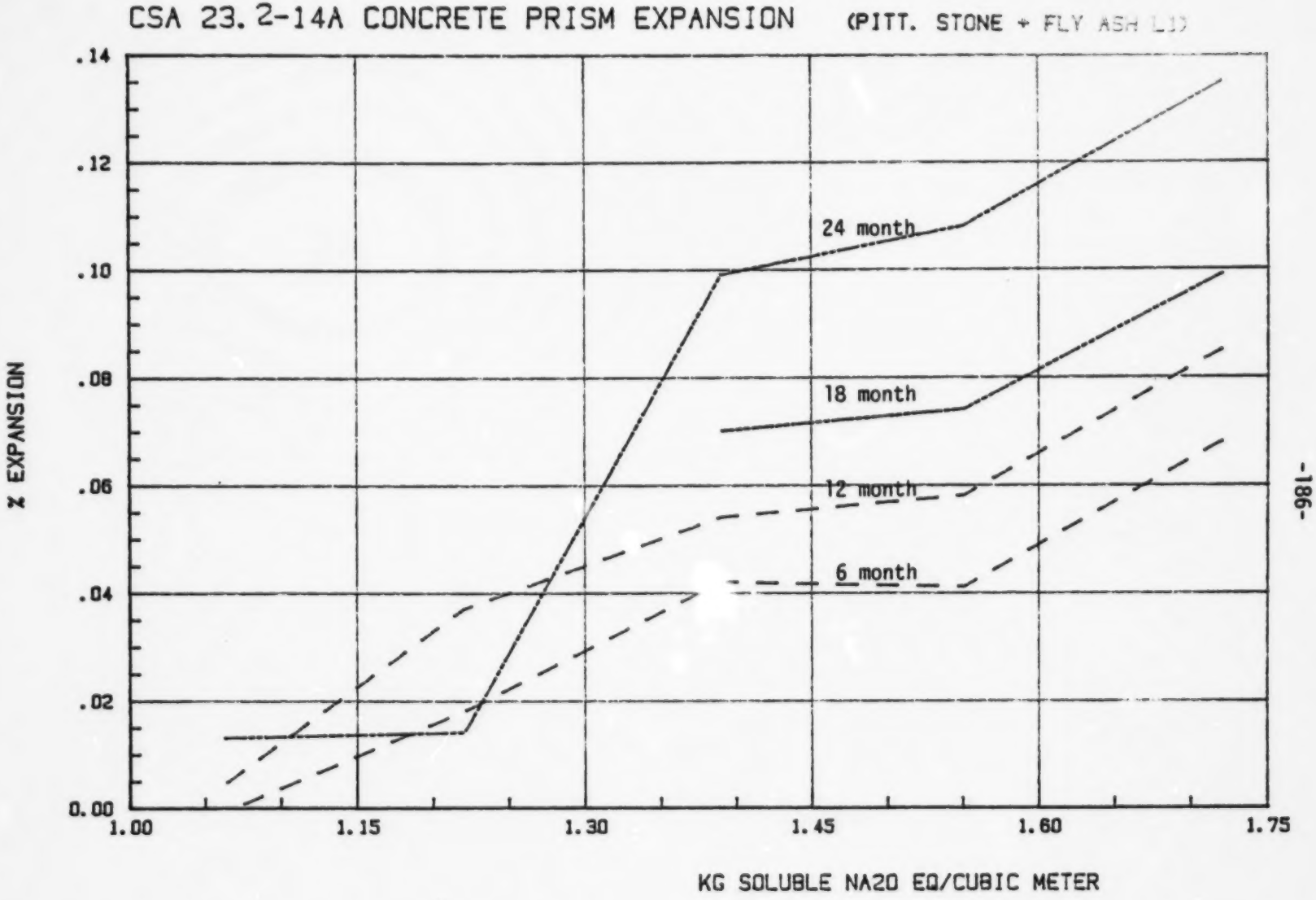

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L1)
% EXPANSION
.14
.12
.10
.08
.06
.04
.02
0.00
1.00
1.15
1.30
1.45
1.60
1.75
24 month
18 month
12 month
6 month
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 102

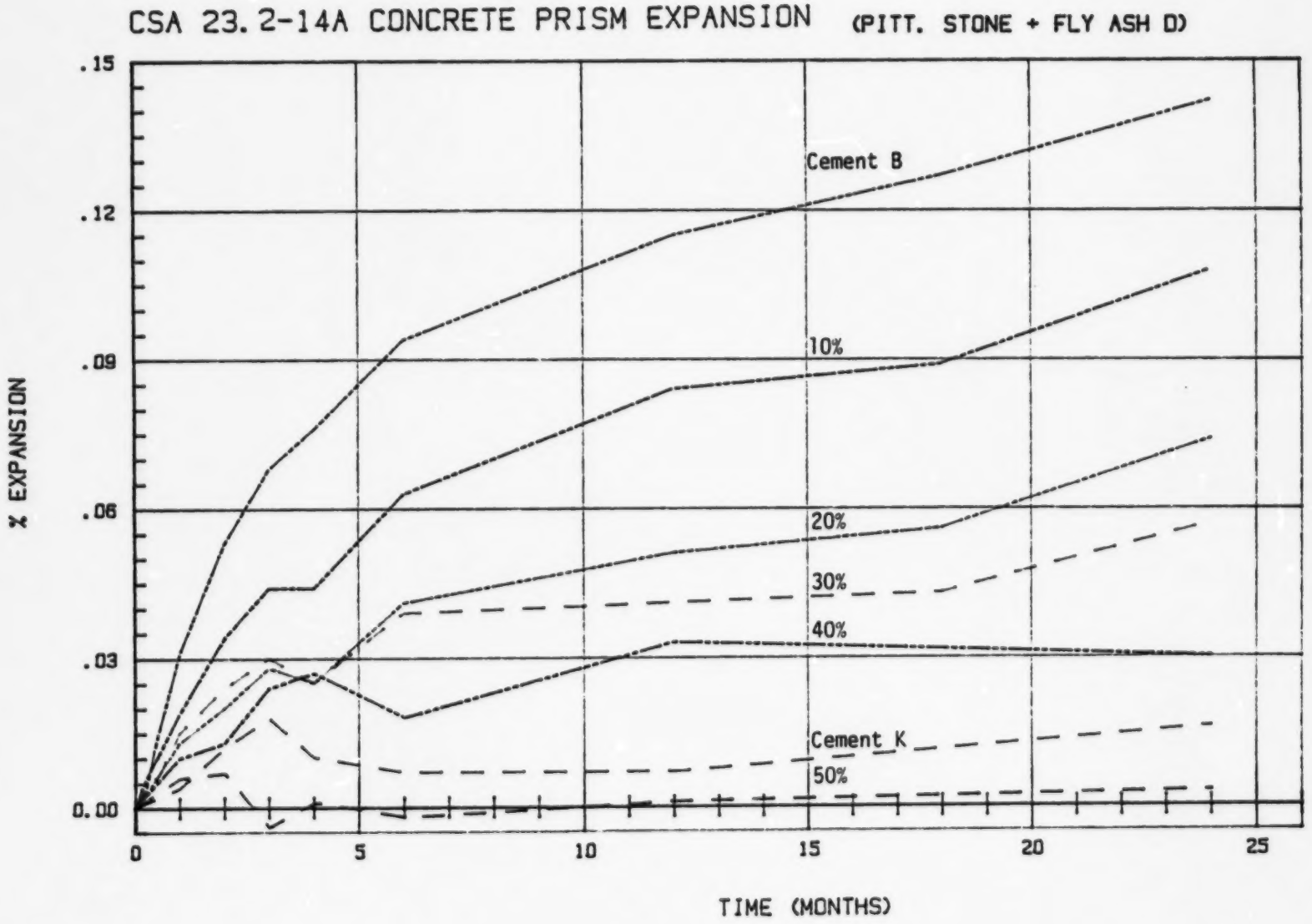

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH D)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 103

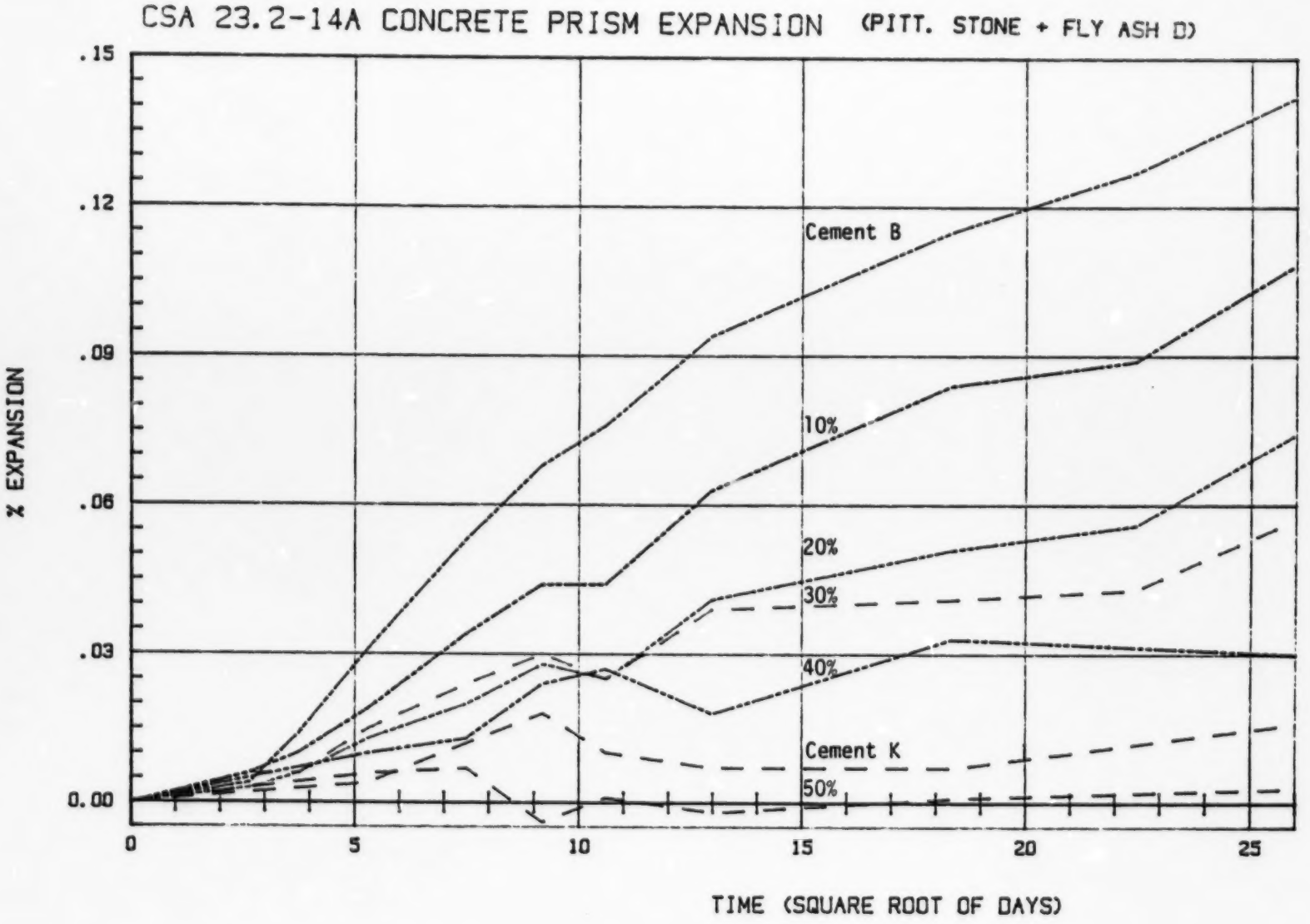

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH D)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 104

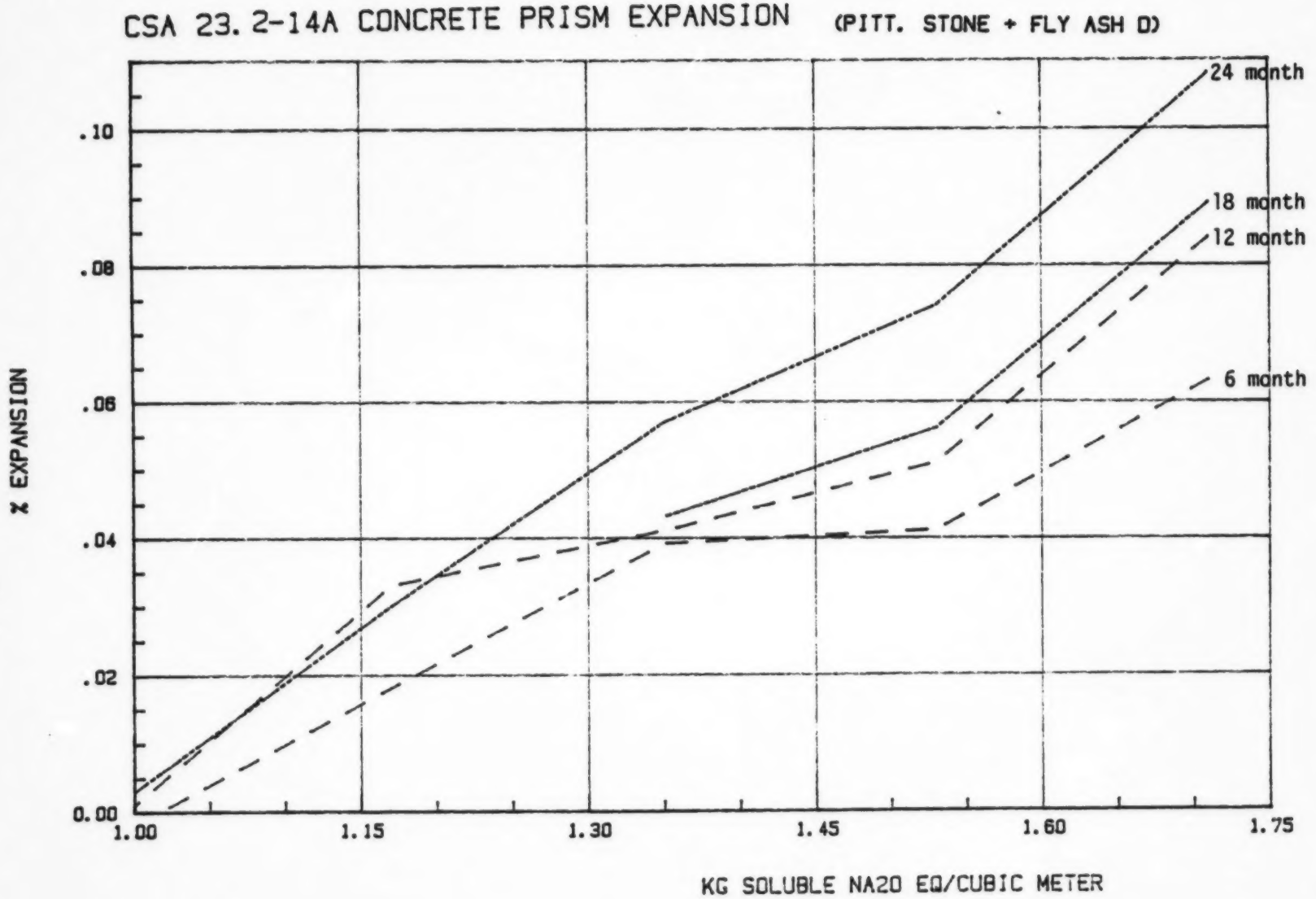

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH D)
24 month
18 month
12 month
6 month
.10
.08
.06
.04
.02
0.00
% EXPANSION
1.00
1.15
1.30
1.45
1.60
1.75
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 105

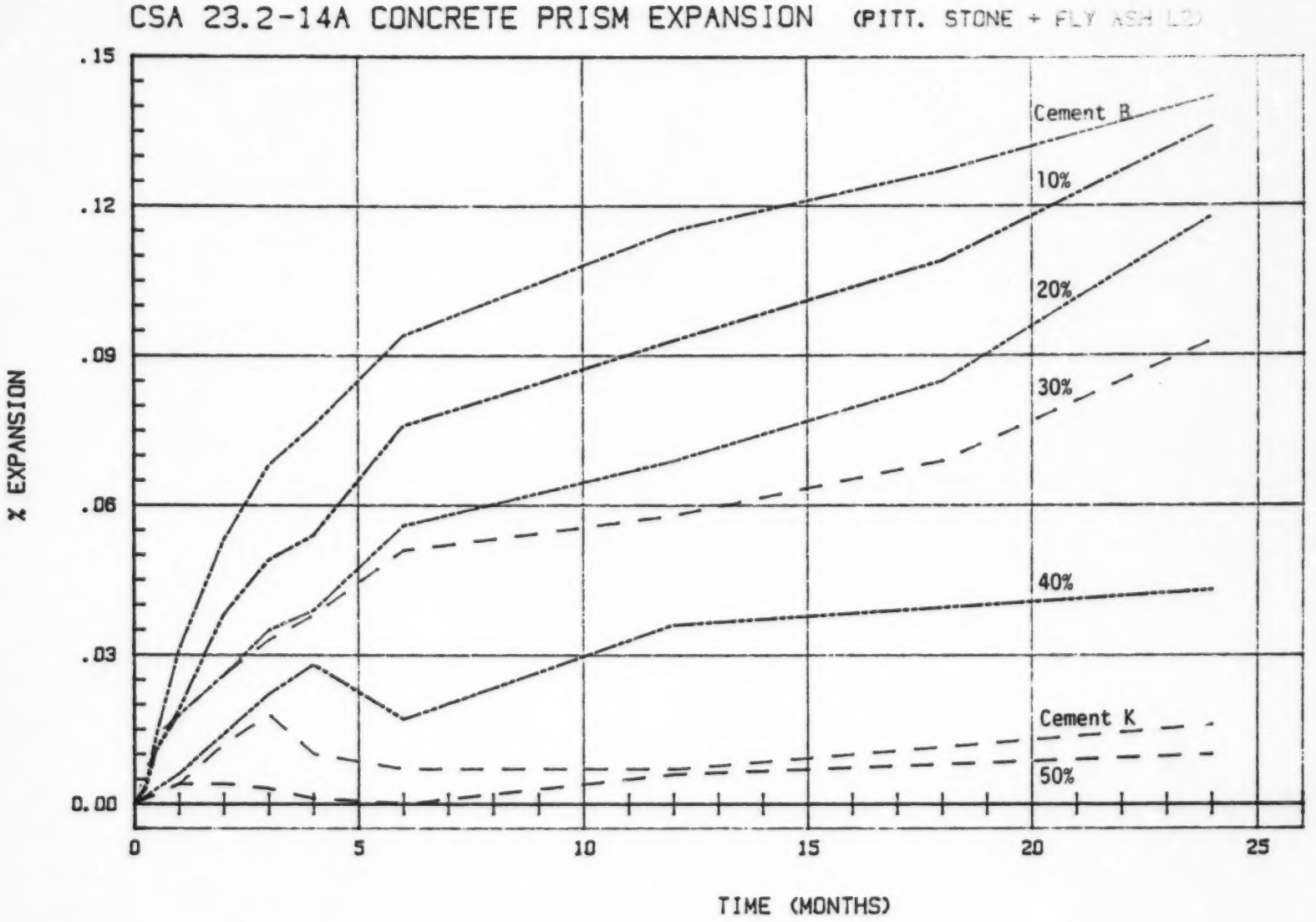

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L2)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 106

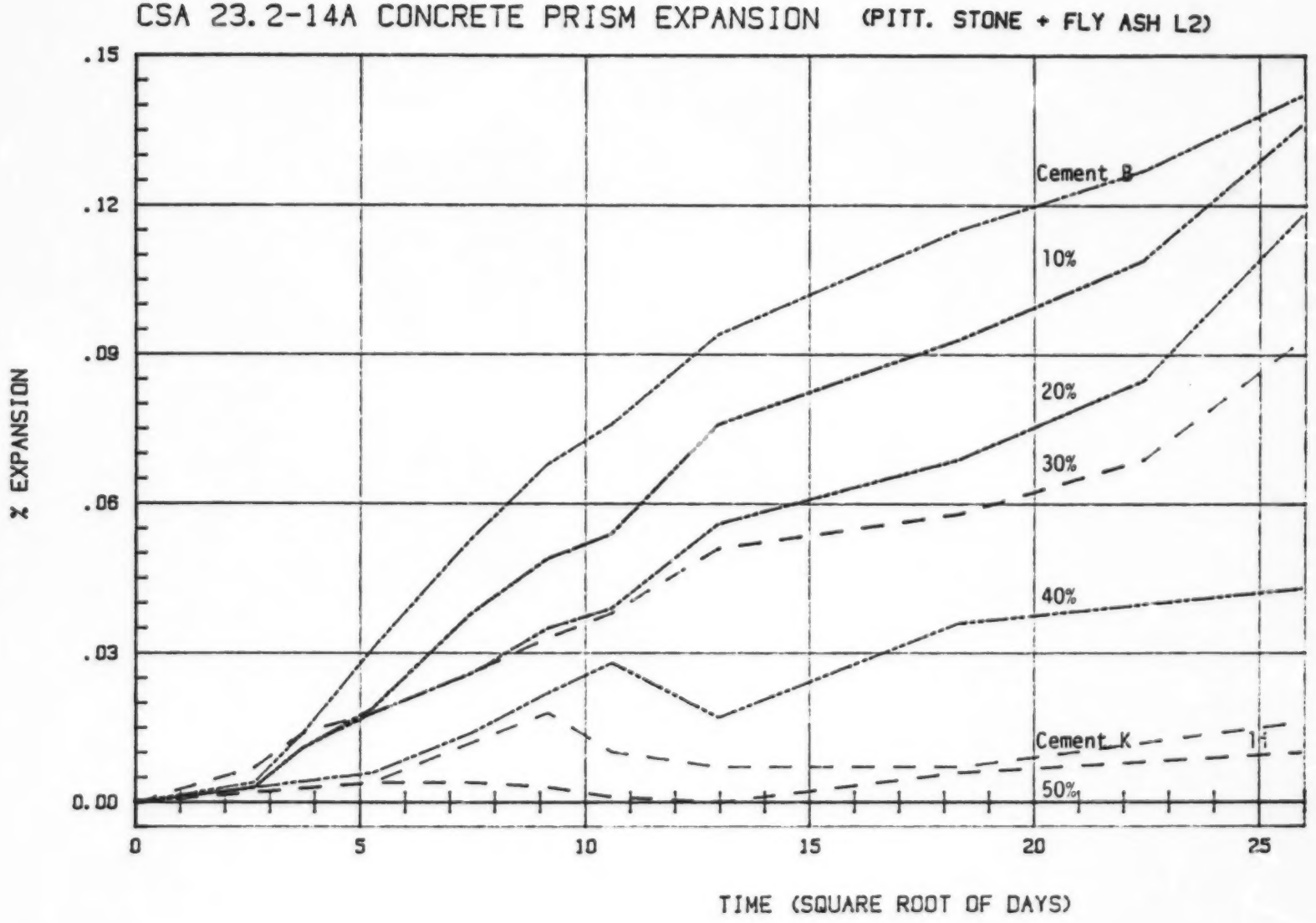

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L2)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
40%
Cement K
15
50%

Figure 107

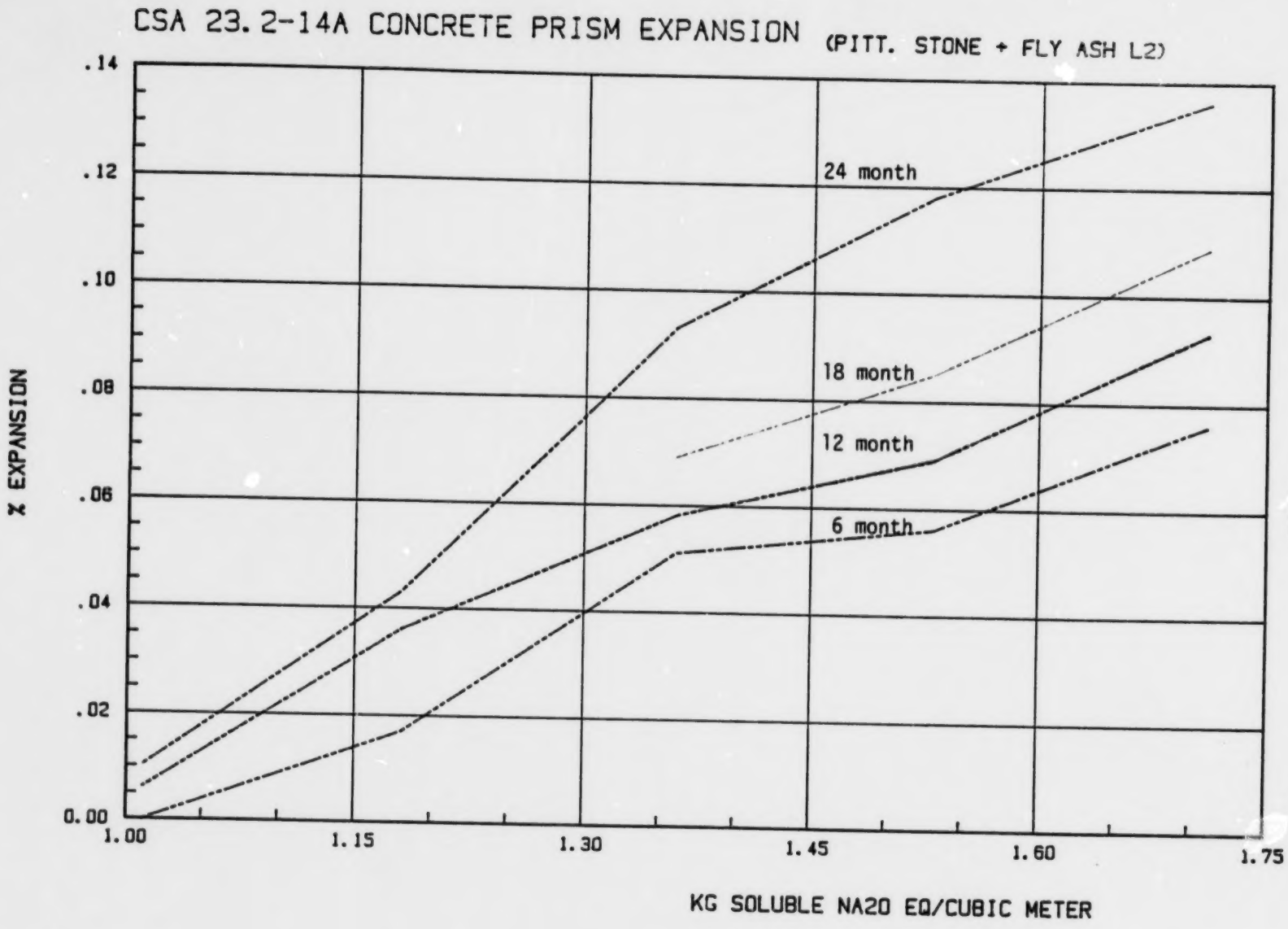

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH L2)
% EXPANSION
.14
.12
.10
.08
.06
.04
.02
0.00
1.00
1.15
1.30
1.45
1.60
1.75
24 month
18 month
12 month
6 month
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 108

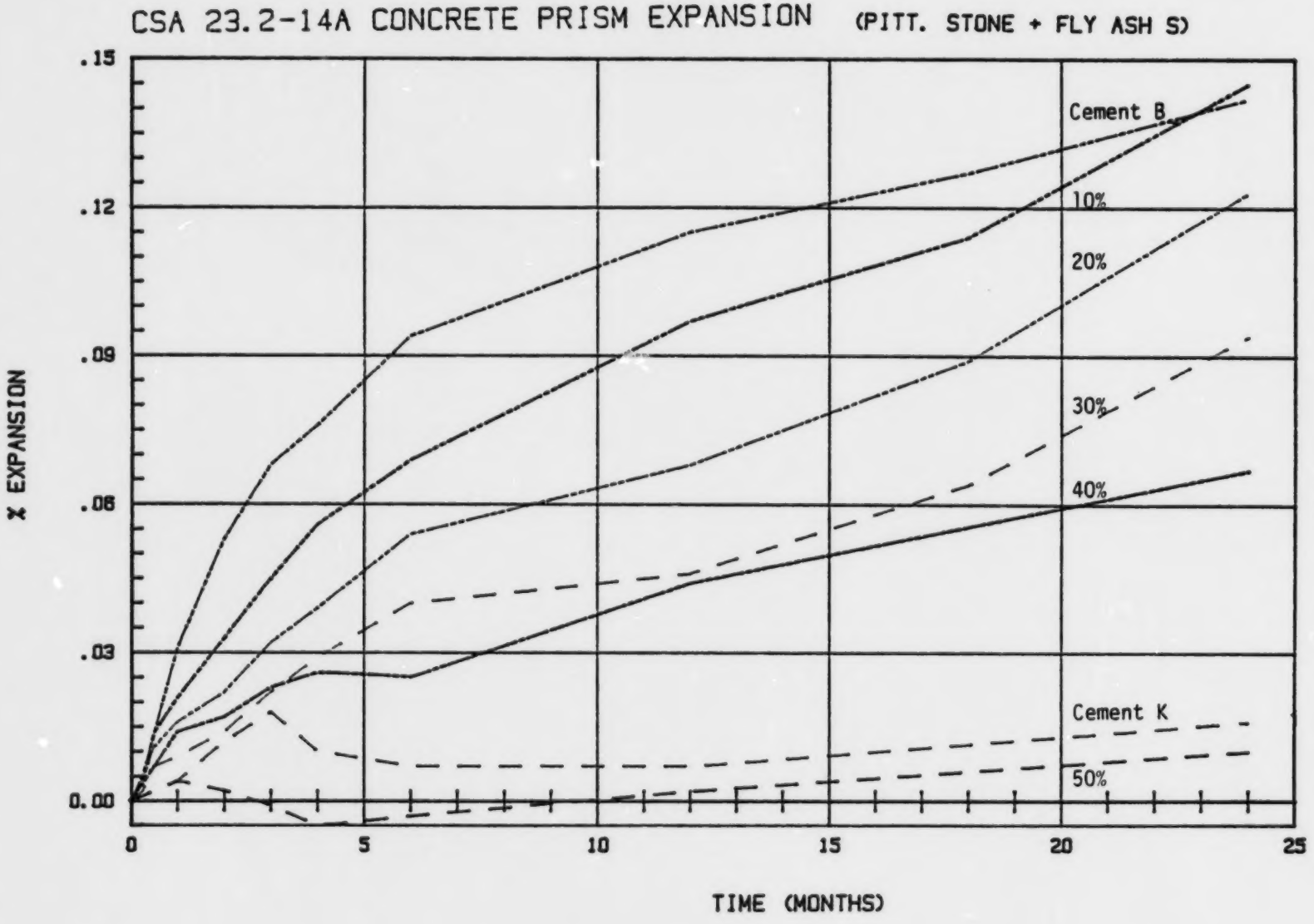

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH S)
.15
.12
.09
.06
.03
0.00
% EXPANSION
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 109

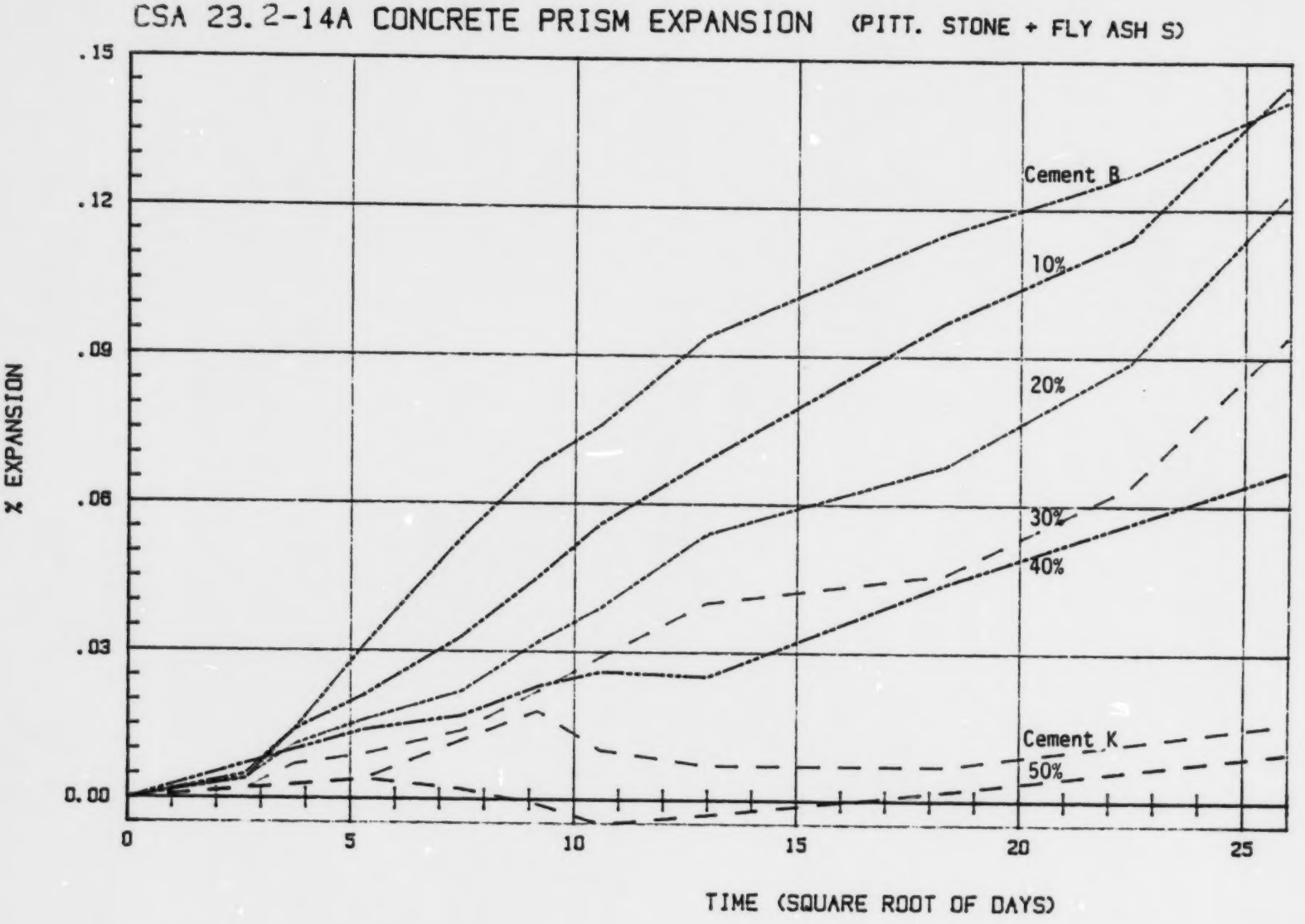

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH S)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
40%
Cement K
50%

Figure 110

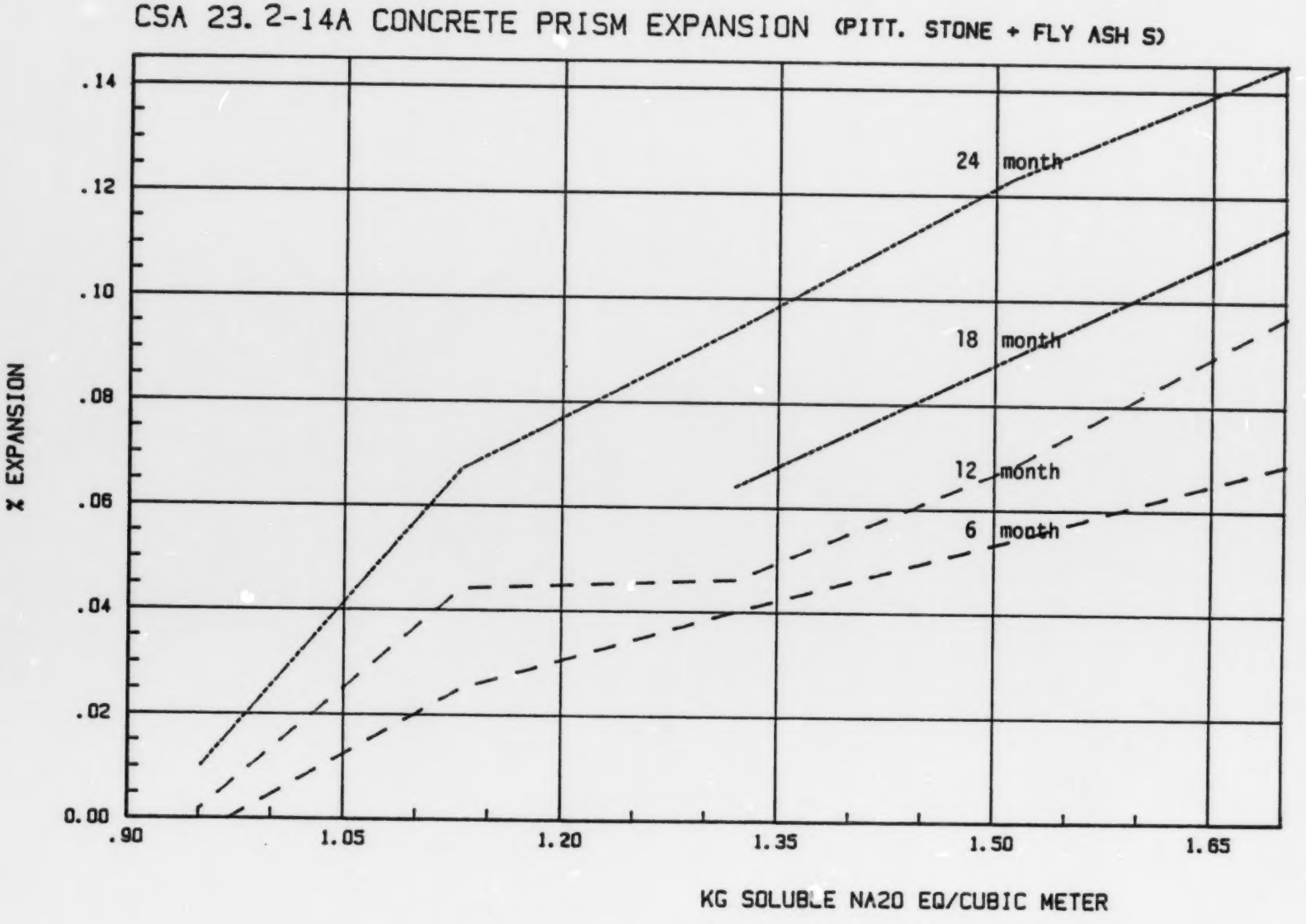

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH S)
% EXPANSION
.14
.12
.10
.08
.06
.04
.02
0.00
.90
1.05
1.20
1.35
1.50
1.65
24 month
18 month
12 month
6 month
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 111

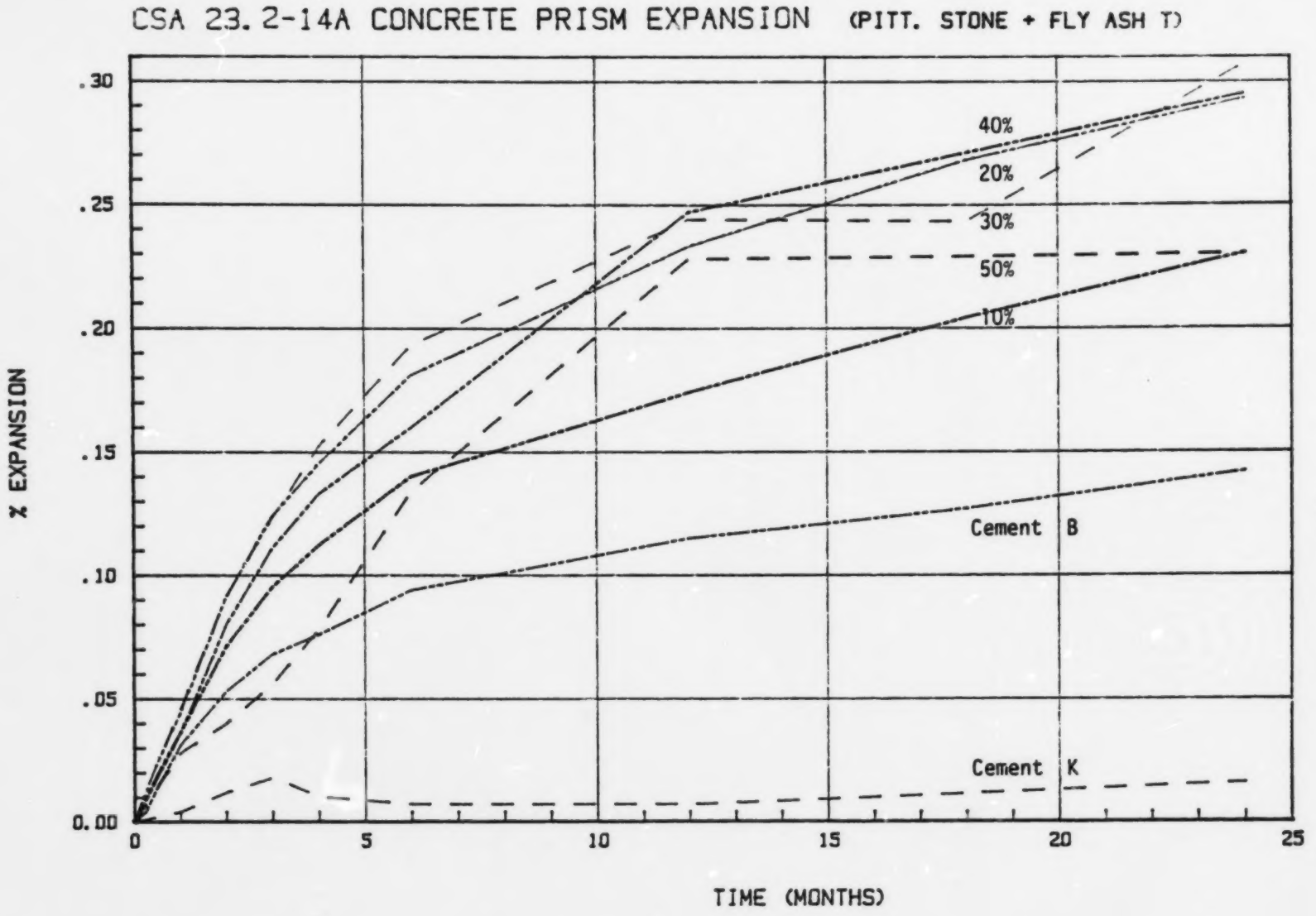

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH T)
% EXPANSION
.30
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (MONTHS)
40%
20%
30%
50%
10%
Cement B
Cement K

Figure 112

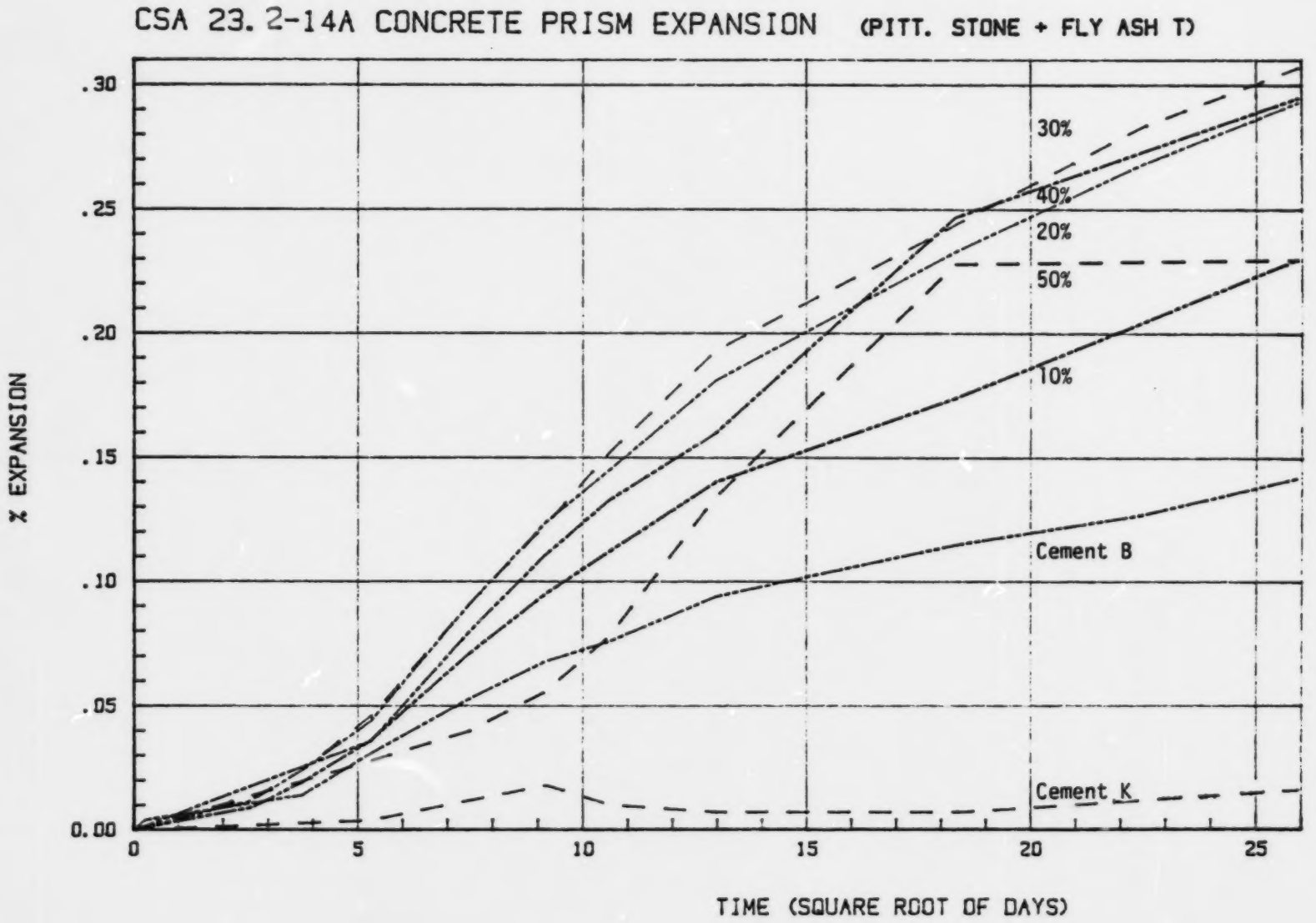

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH T)
% EXPANSION
.30
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
30%
40%
20%
50%
10%
Cement B
Cement K

Figure 113

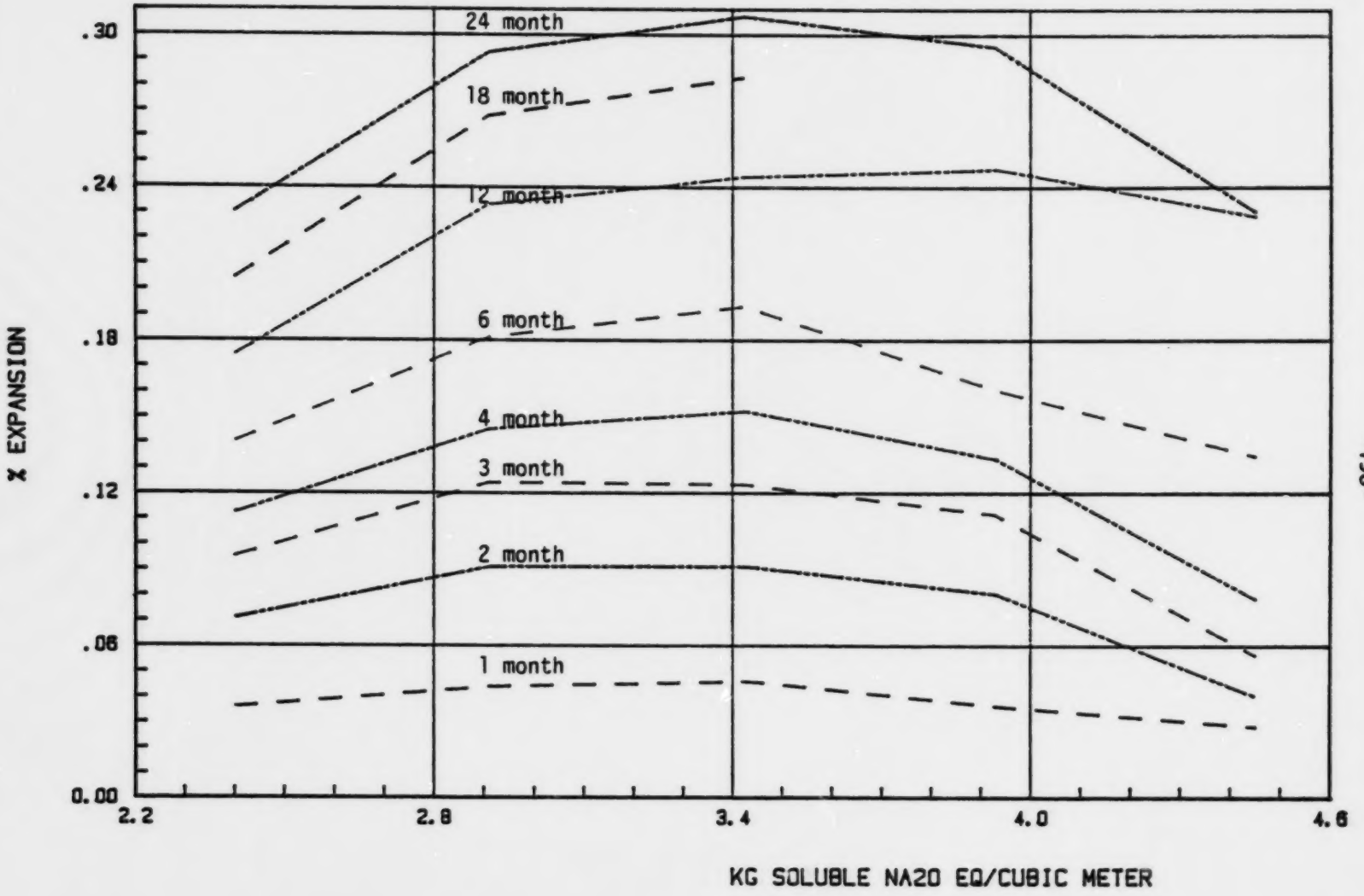

CSA 23.2-14A CONCRETE PRISM EXPANSION . (PITT. STONE + FLY ASH I)
24 month
18 month
12 month
6 month
4 month
3 month
2 month
1 month
.30
.24
.18
.12
.06
0.00
% EXPANSION
2.2
2.8
3.4
4.0
4.6
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 114

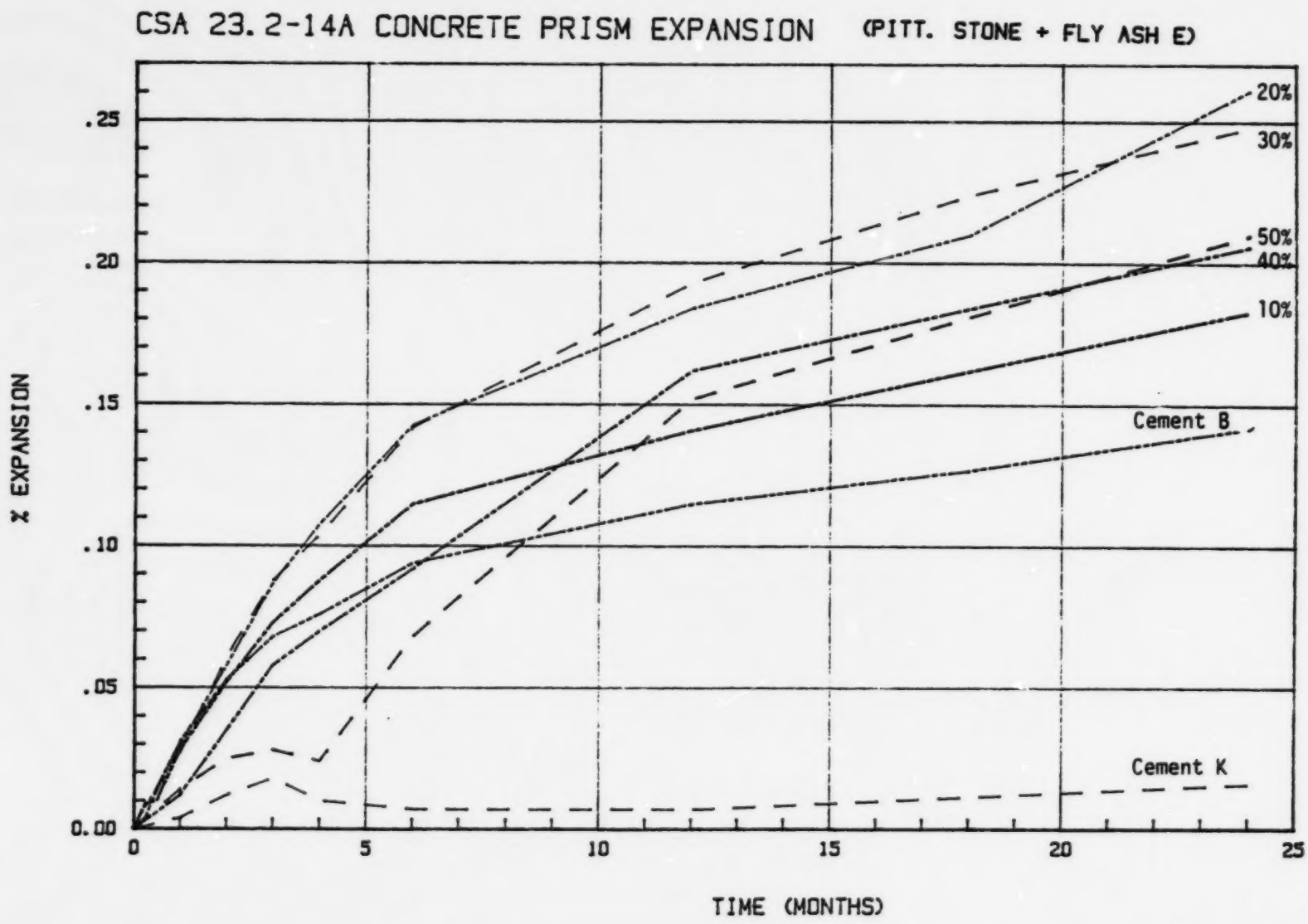

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH E)
% EXPANSION
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (MONTHS)
20%
30%
50%
40%
10%
Cement B
Cement K

Figure 115

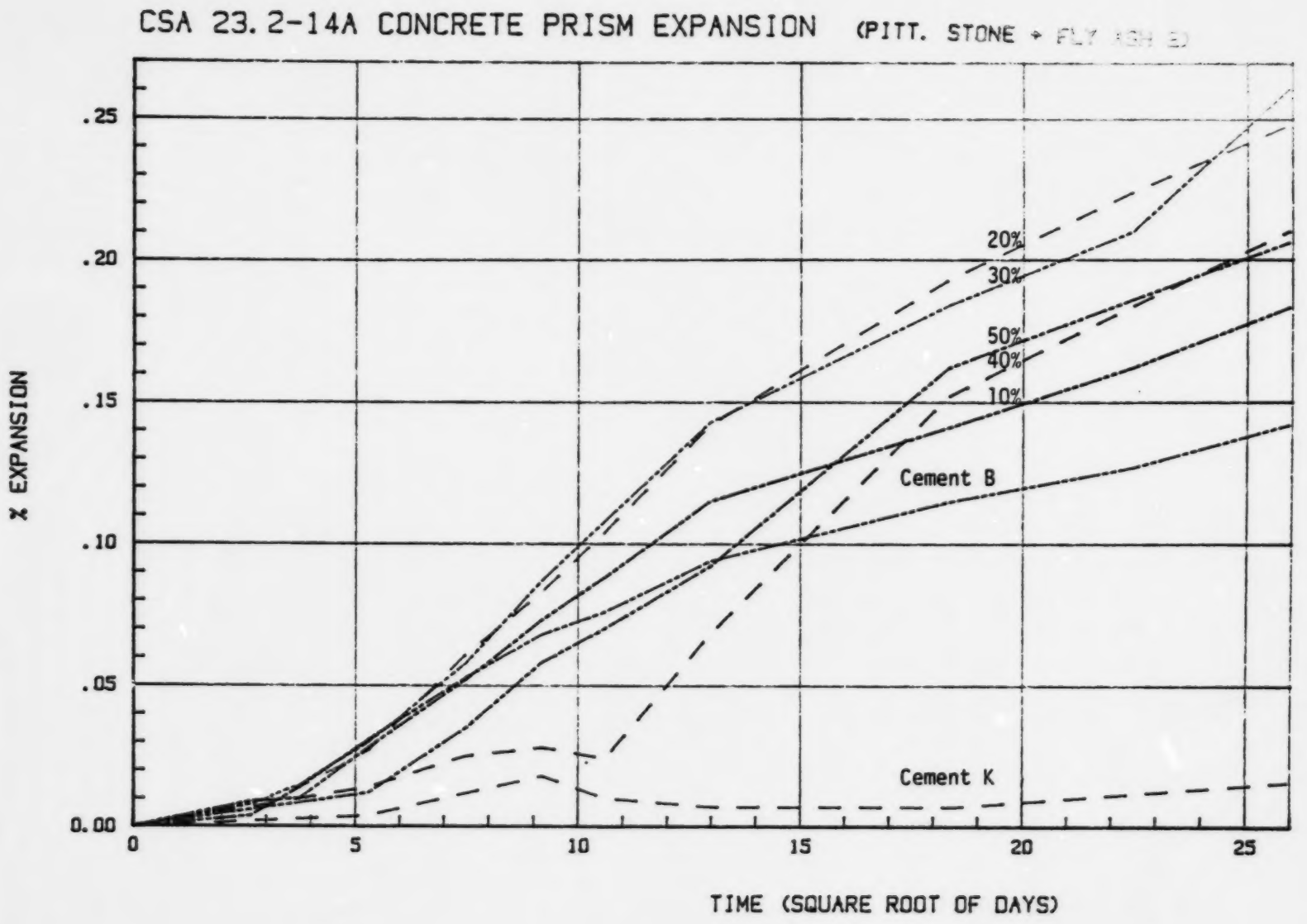

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH E)
% EXPANSION
.25
.20
.15
.10
.05
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
20%
30%
50%
40%
10%
Cement B
Cement K

Figure 116

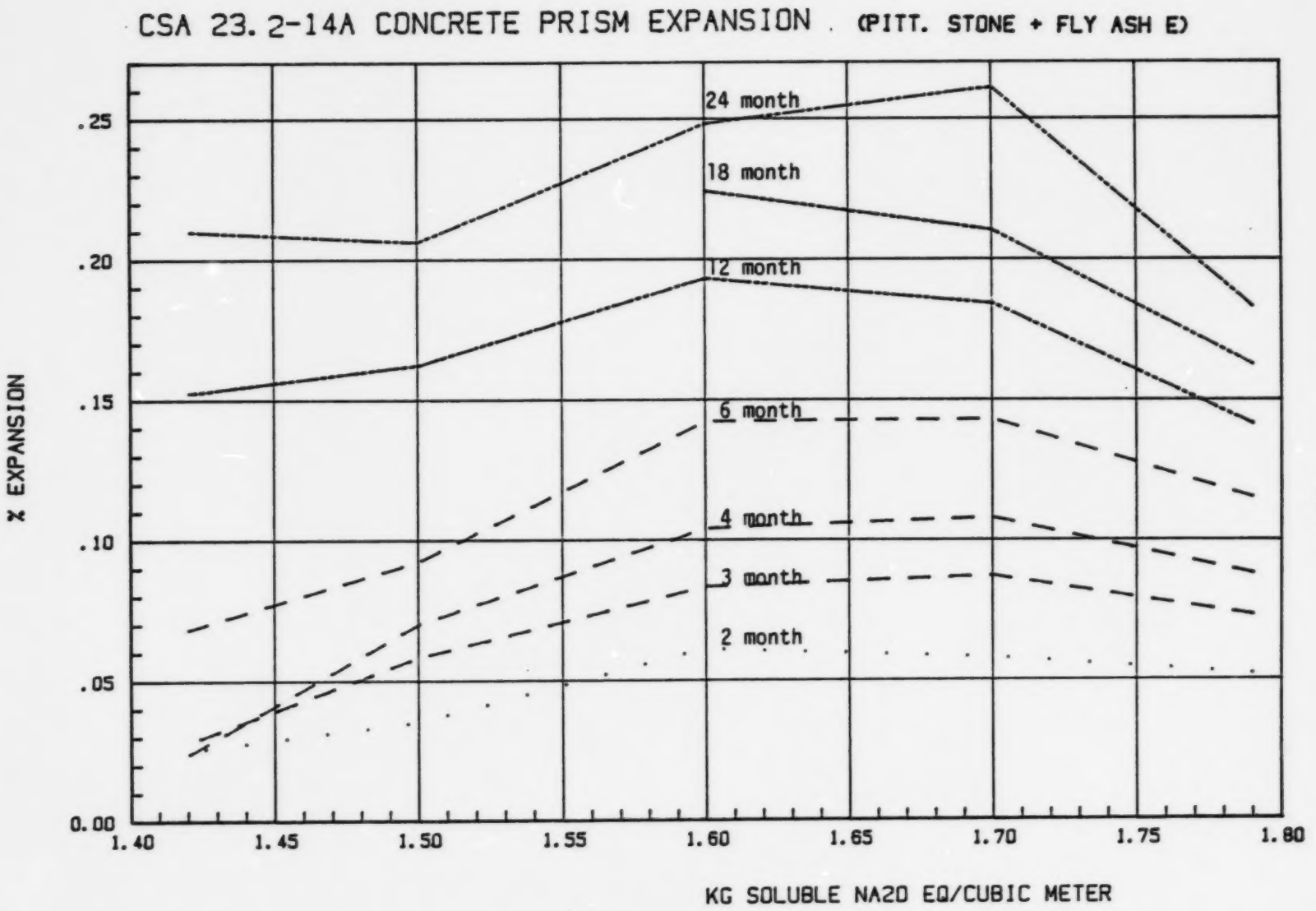
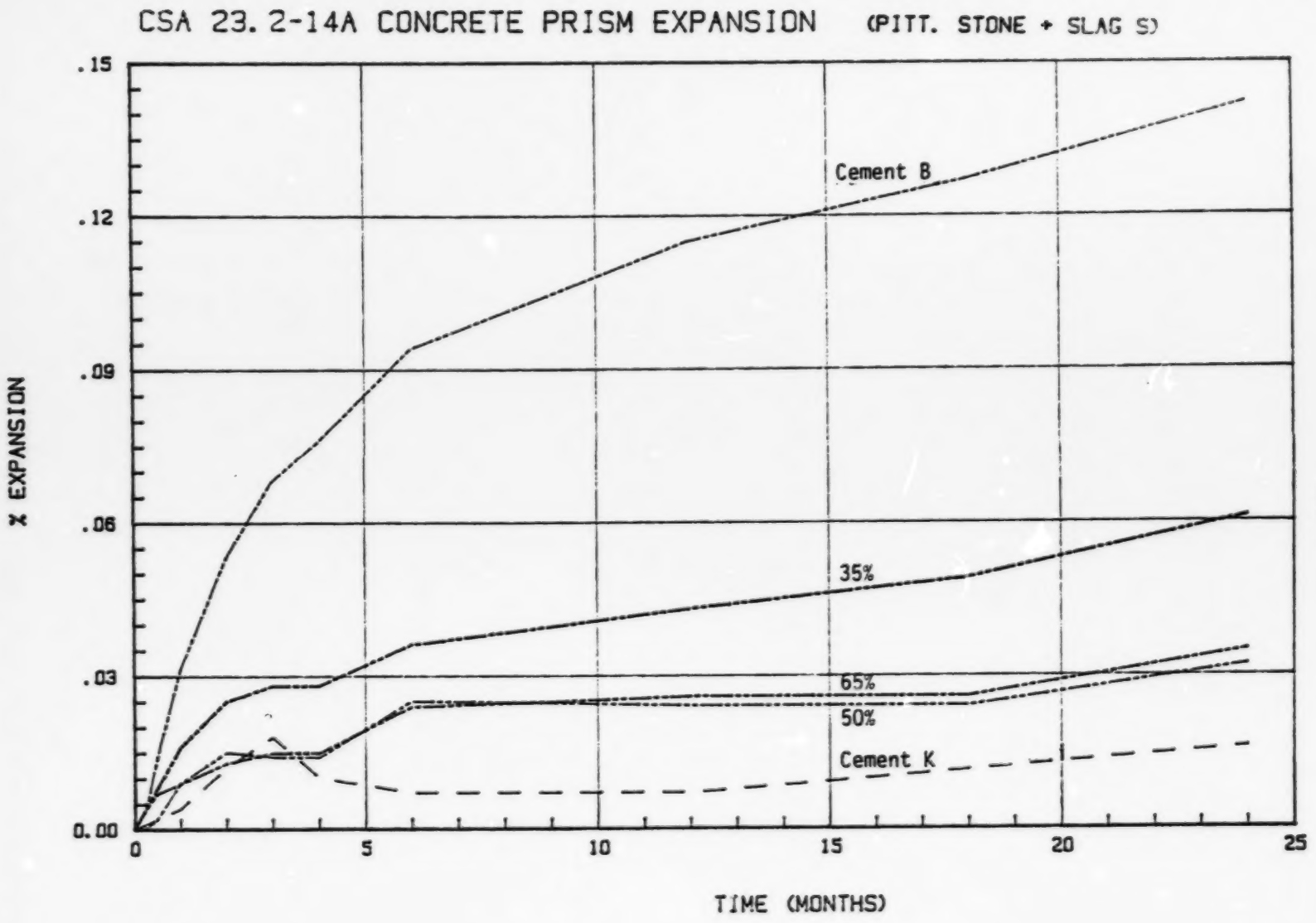

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + FLY ASH E)
% EXPANSION
.25
.20
.15
.10
.05
0.00
1.40
1.45
1.50
1.55
1.60
1.65
1.70
1.75
1.80
24 month
18 month
12 month
6 month
4 month
3 month
2 month
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 117


CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG S)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
35%
65%
50%
Cement K

Figire 118

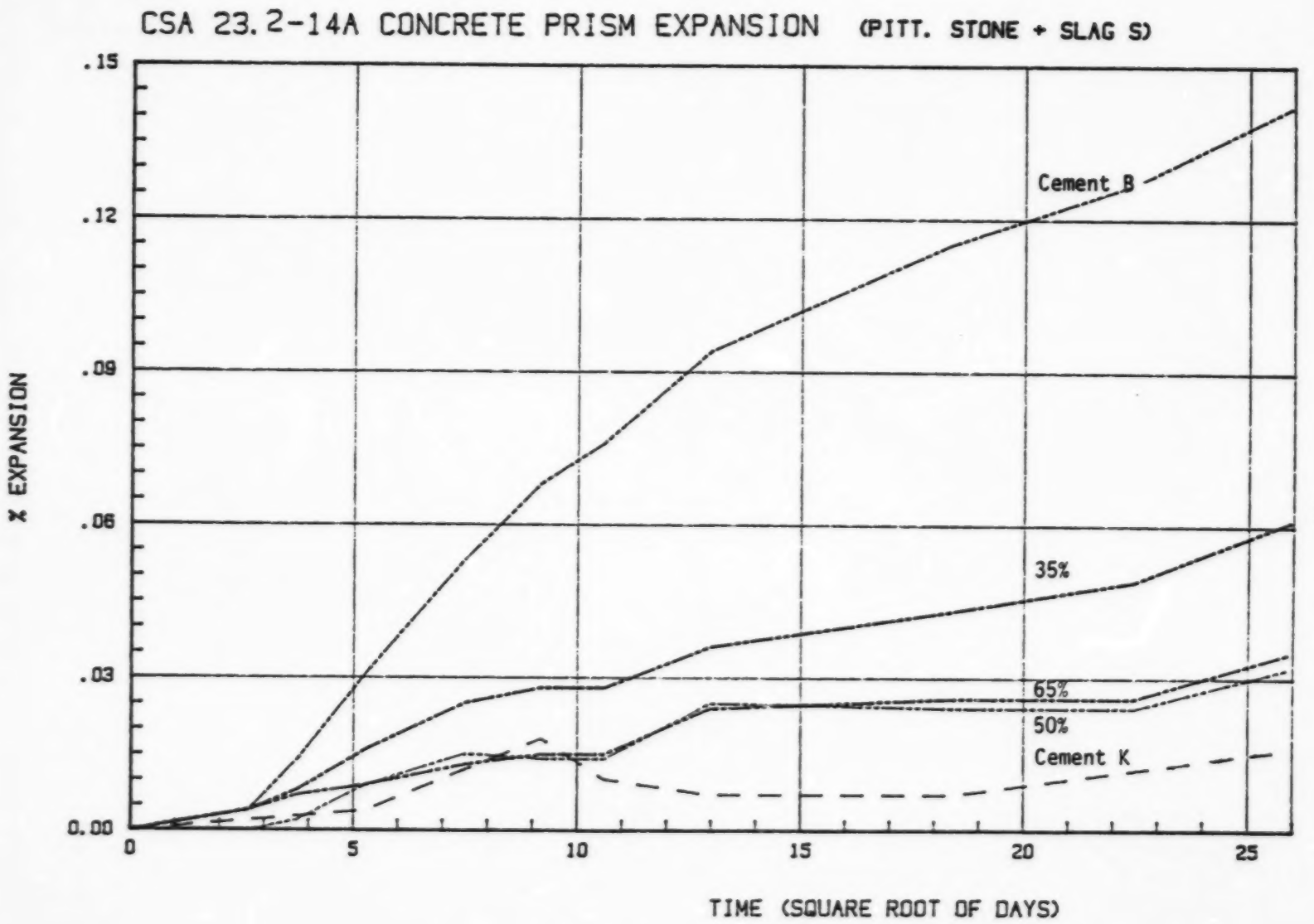

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG S)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
35%
65%
50%
Cement K

Figure 119

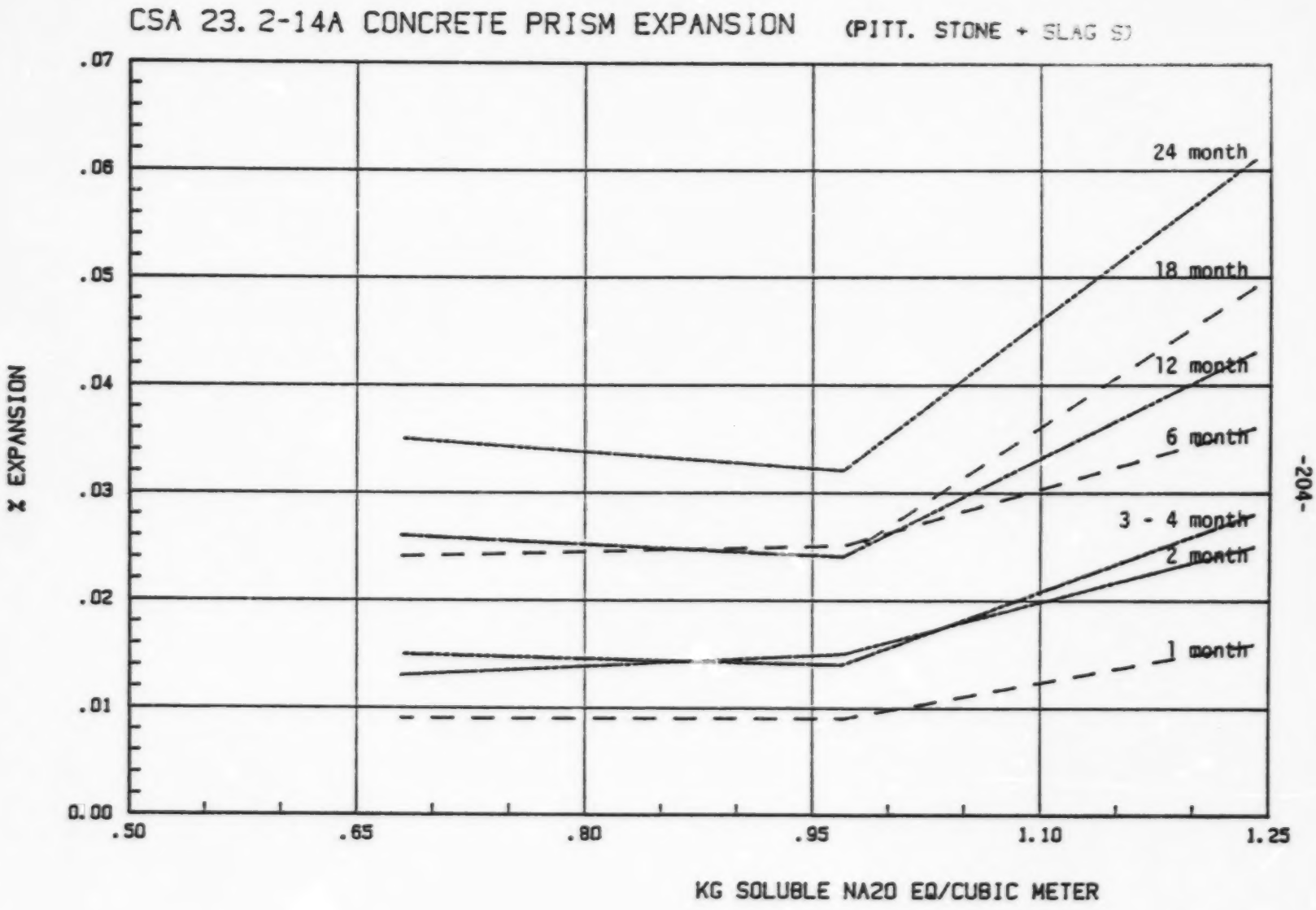

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG S)
% EXPANSION
.07
.06
.05
.04
.03
.02
.01
0.00
.50
.65
.80
.95
1.10
1.25
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
6 month
3 - 4 month
2 month
1 month

Figure 120

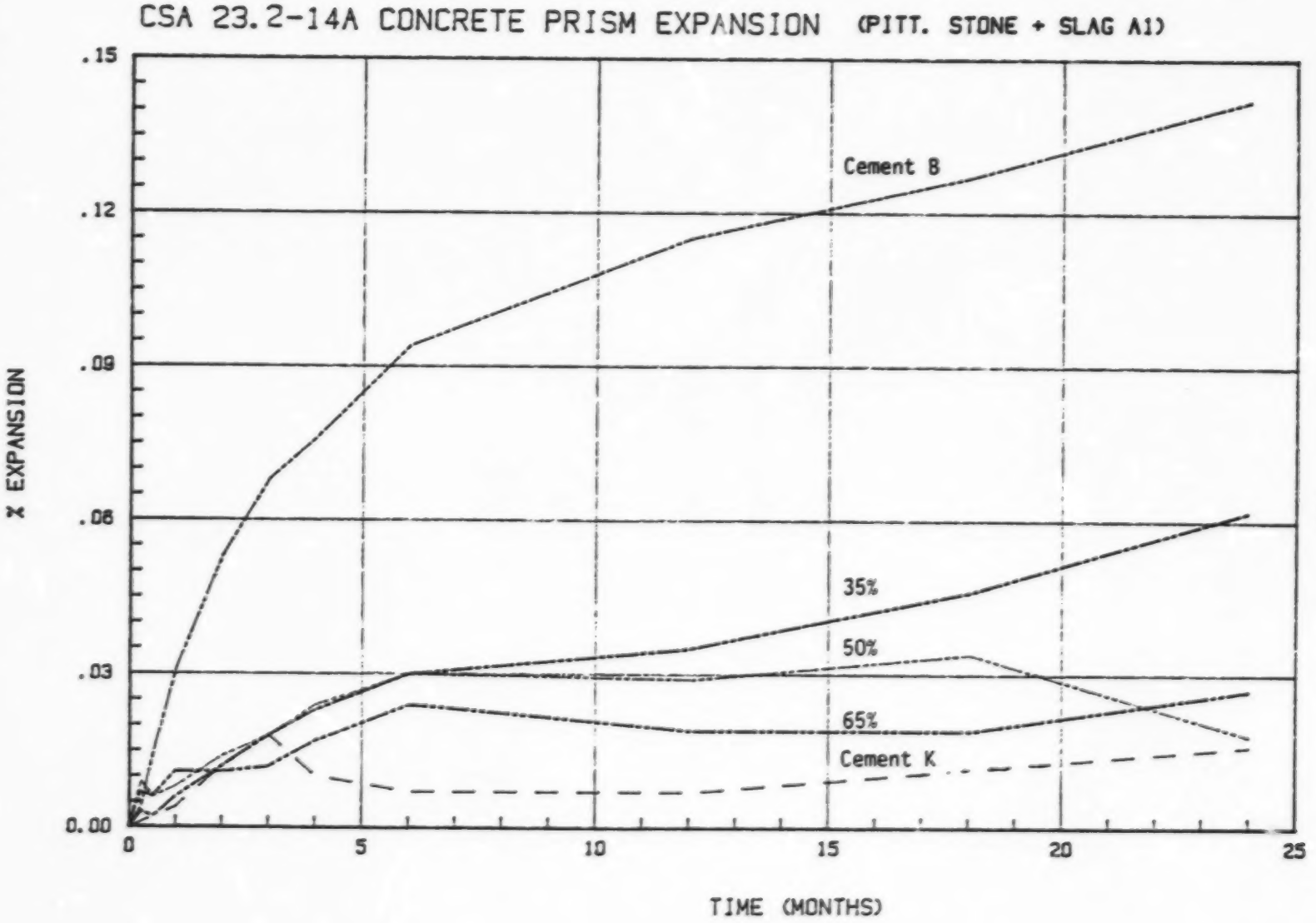

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG A1)
.15
.12
.09
.06
.03
0.00
% EXPANSION
Cement B
35%
50%
65%
Cement K
0
5
10
15
20
25
TIME (MONTHS)

Figure 121

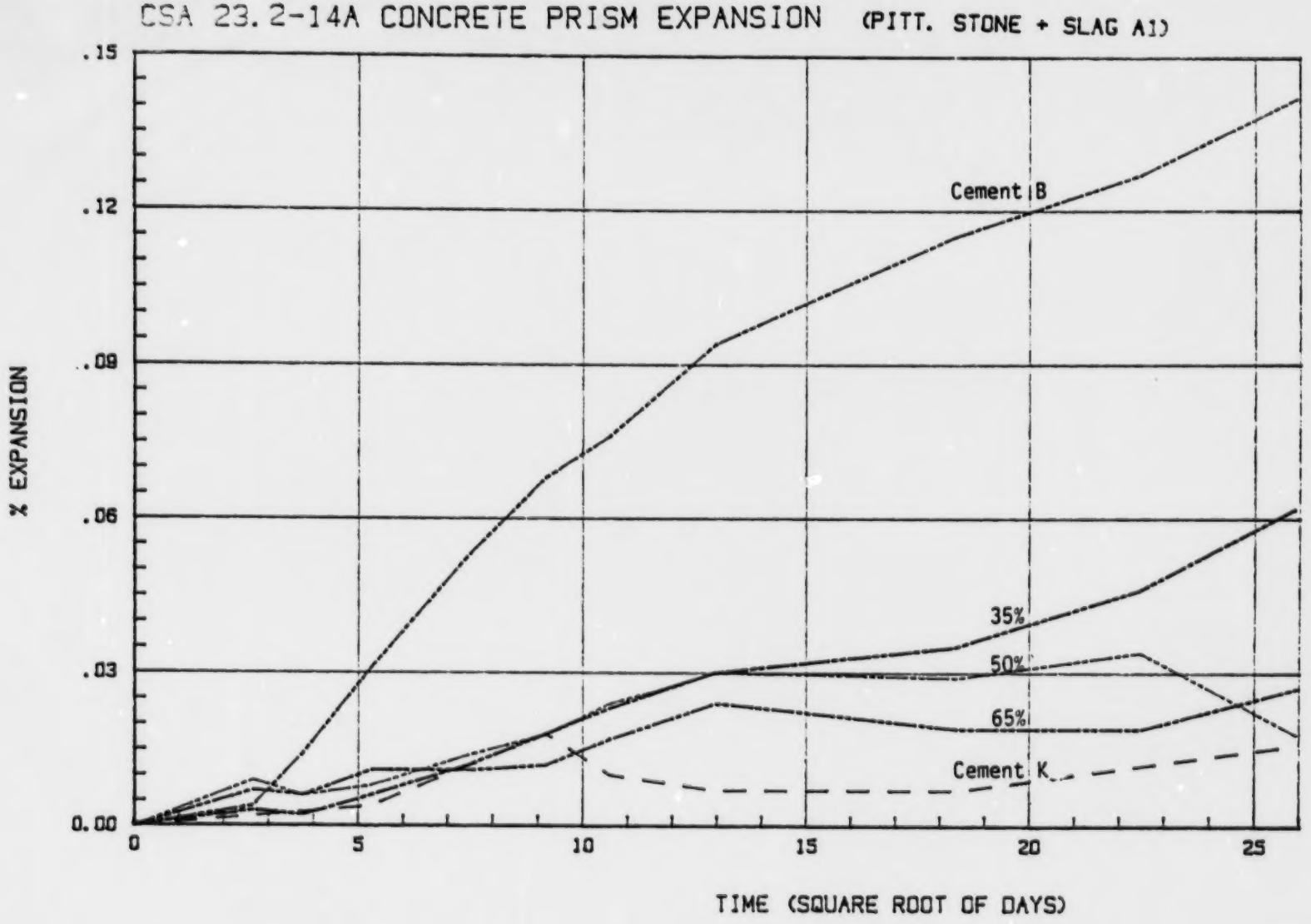

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG A1)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
35%
50%
65%
Cement K

Figure 122

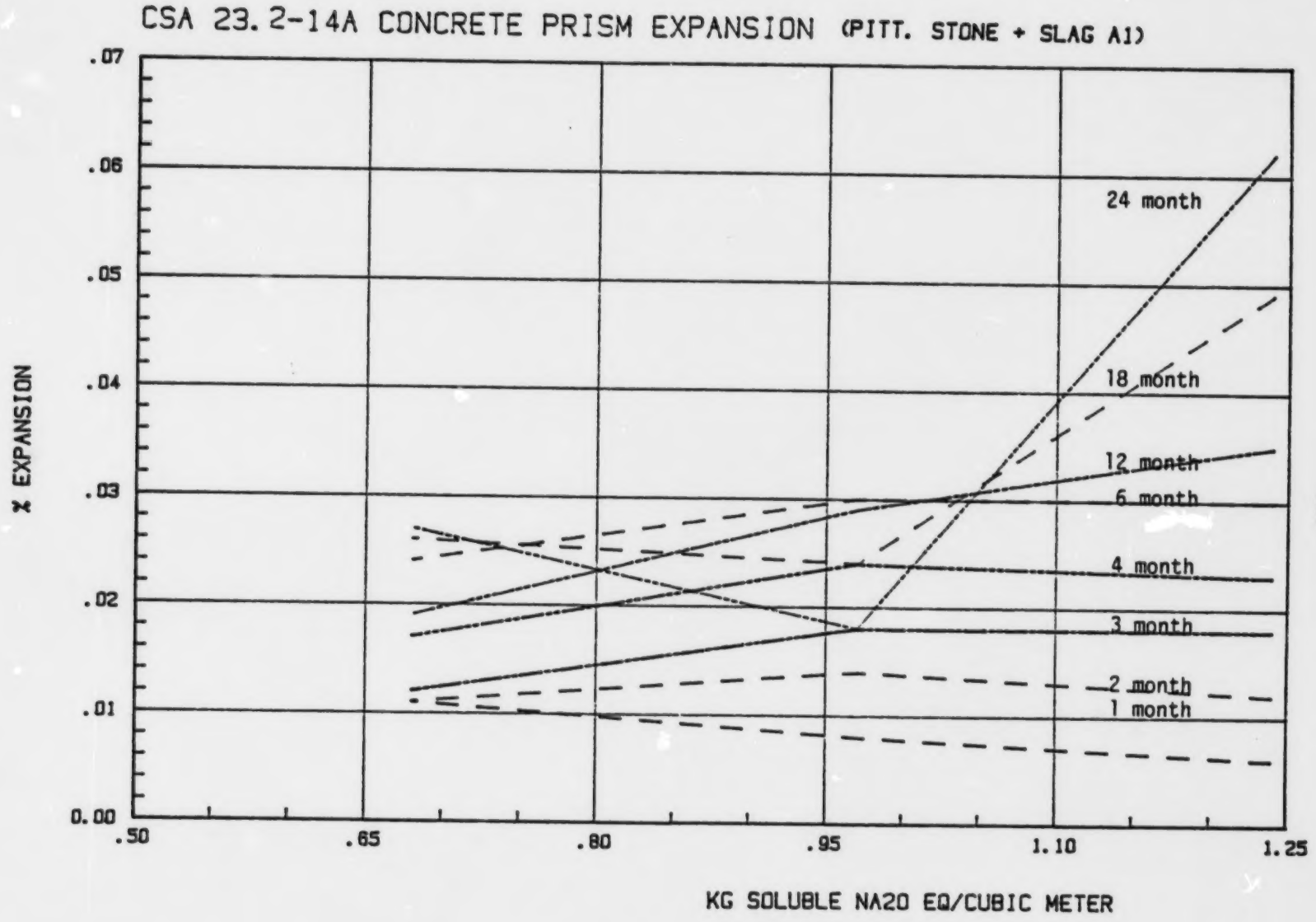

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + SLAG A1)
% EXPANSION
.07
.06
.05
.04
.03
.02
.01
0.00
.50
.65
.80
.95
1.10
1.25
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
6 month
4 month
3 month
2 month
1 month

Figure 123

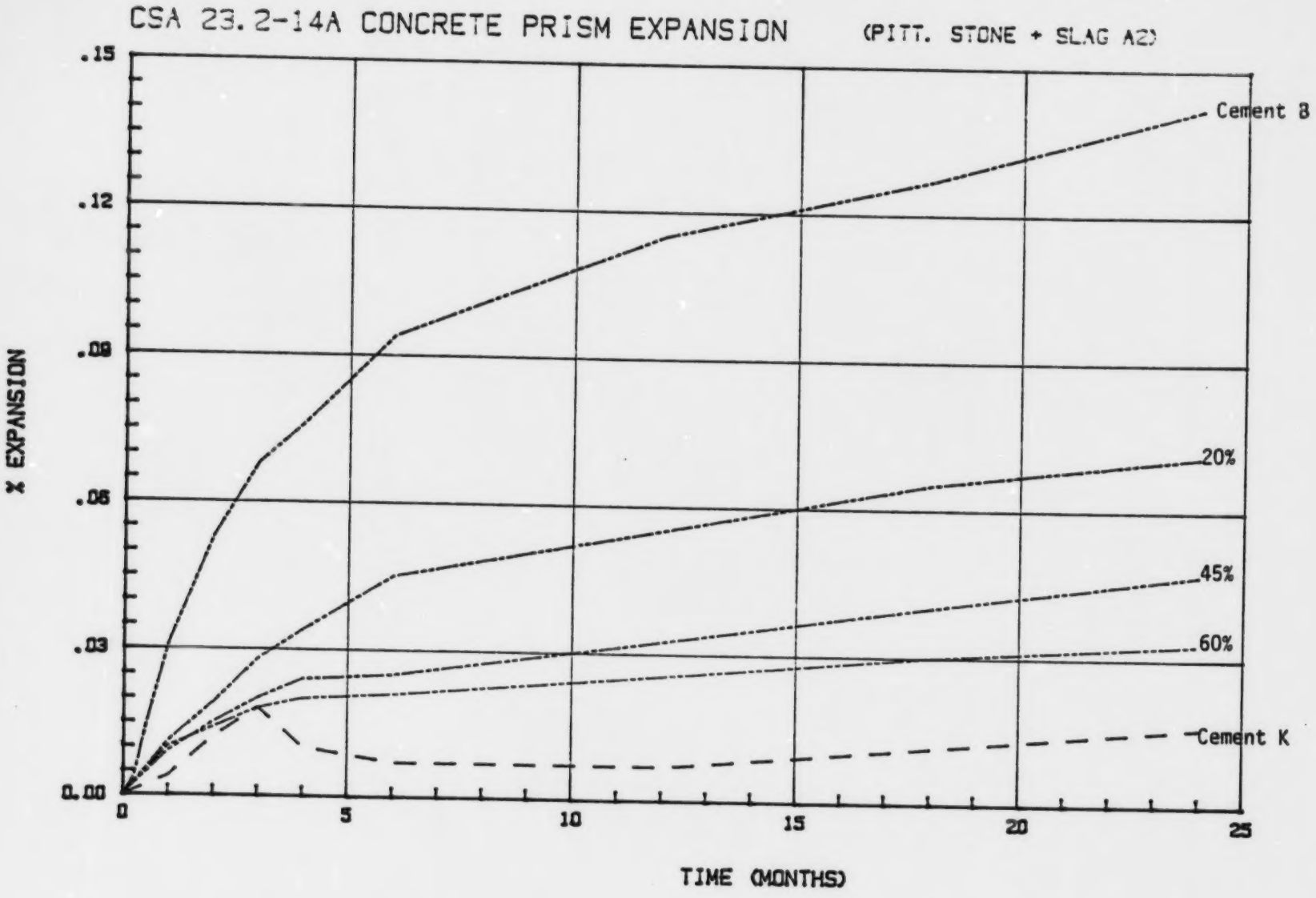

CSA 23.2-14A CONCRETE PRISM EXPANSION
(PITT. STONE + SLAG A2)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
20%
45%
60%
Cement K

Figure 124

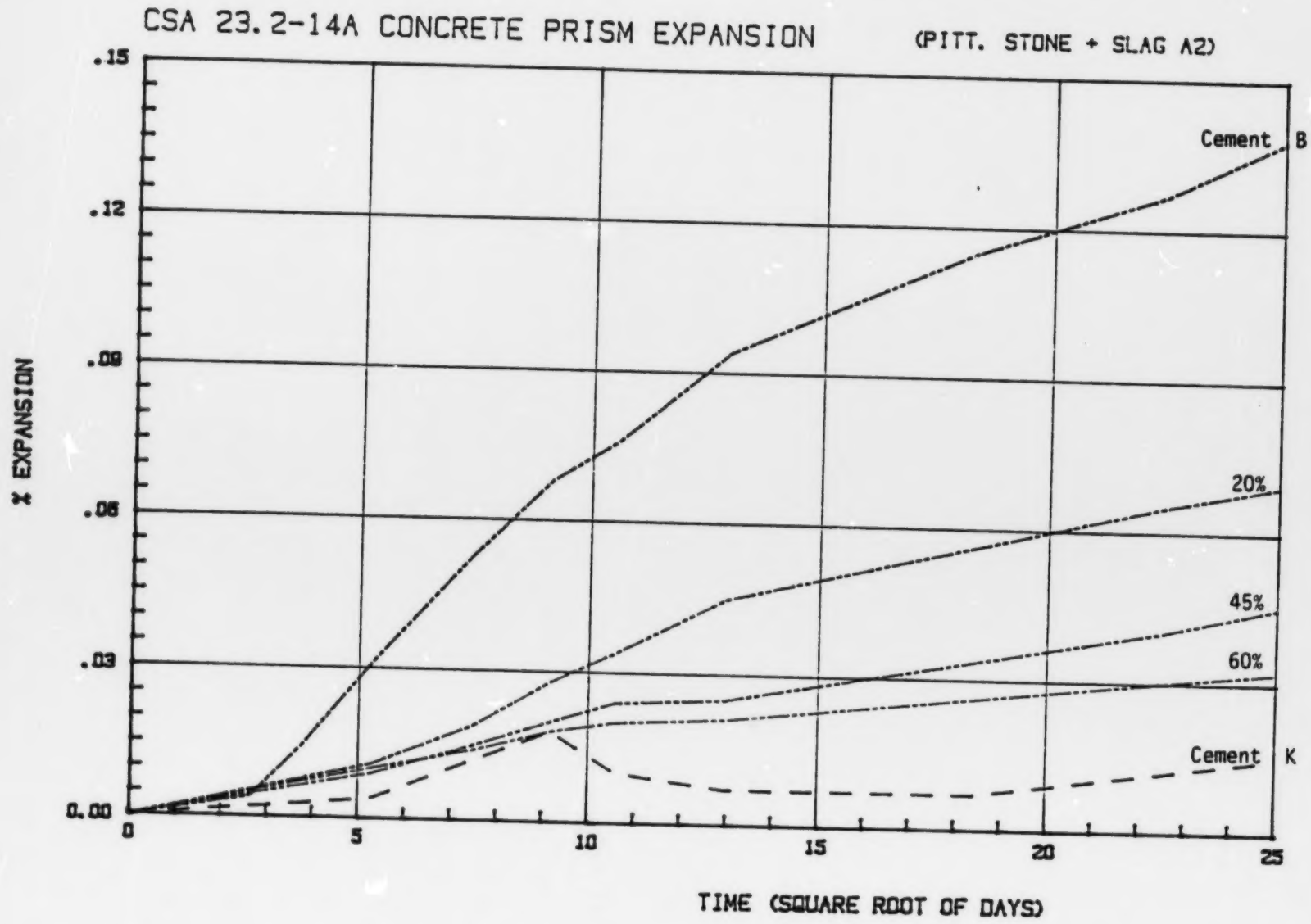

CSA 23.2-14A CONCRETE PRISM EXPANSION
(PITT. STONE + SLAG A2)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
20%
45%
60%
Cement K

Figure 125

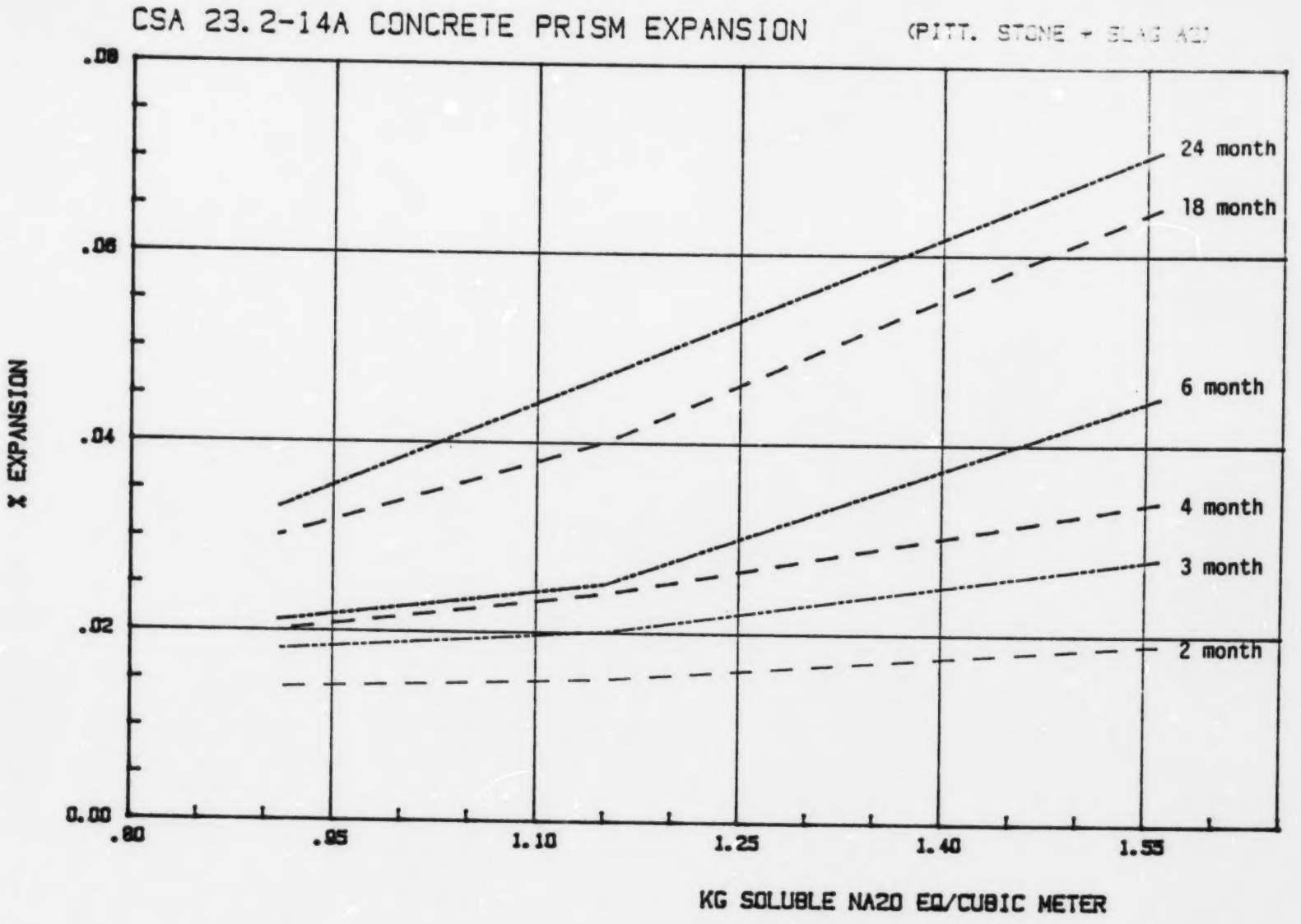

CSA 23.2-14A CONCRETE PRISM EXPANSION
(PITT. STONE + SLAG AGG
% EXPANSION
.08
.06
.04
.02
0.00
.80
.95
1.10
1.25
1.40
1.55
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
6 month
4 month
3 month
2 month

Figure 126

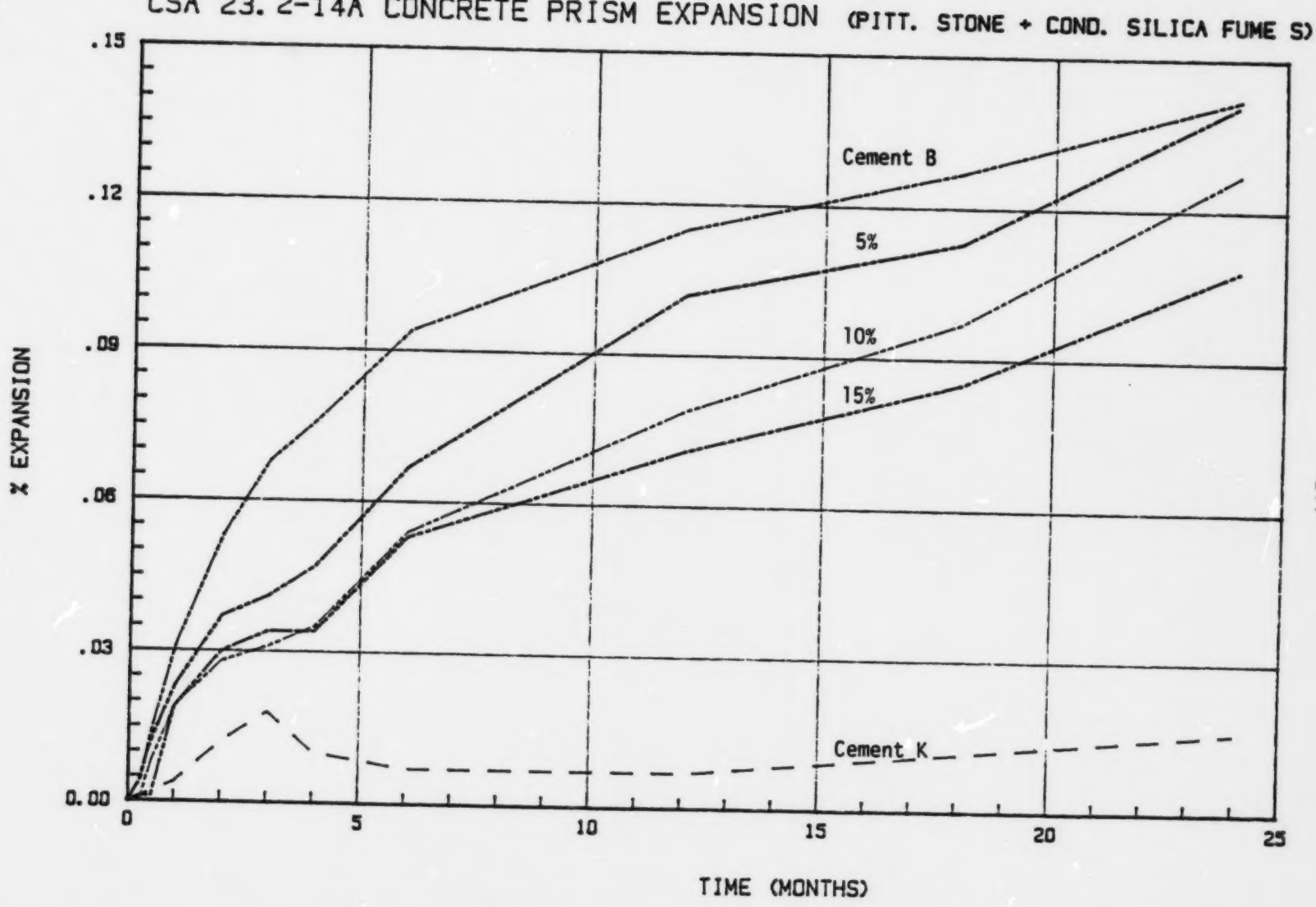

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME S)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
5%
10%
15%
Cement K

Figure 127

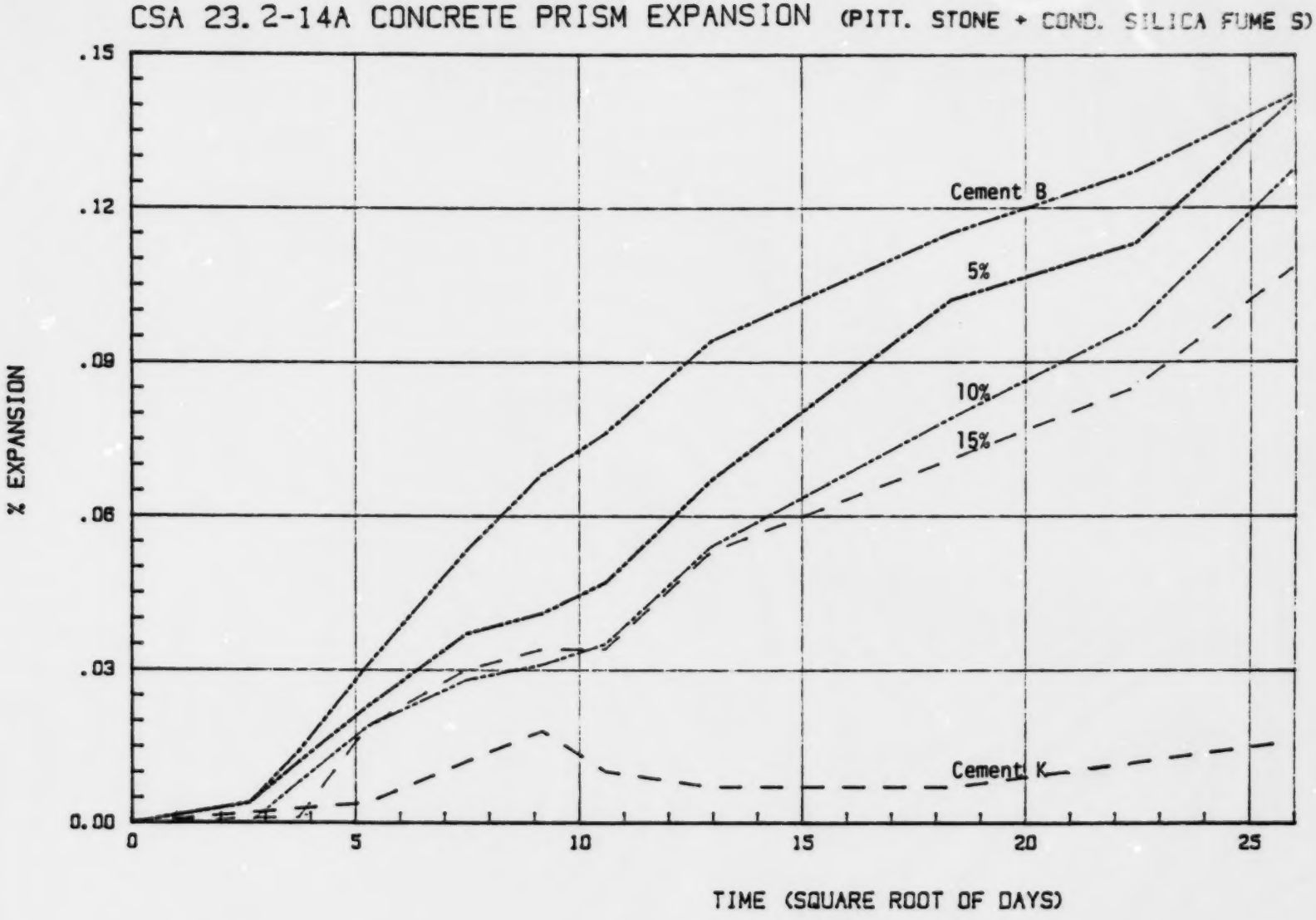

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME S)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
5%
10%
15%
Cement K

Figure 128

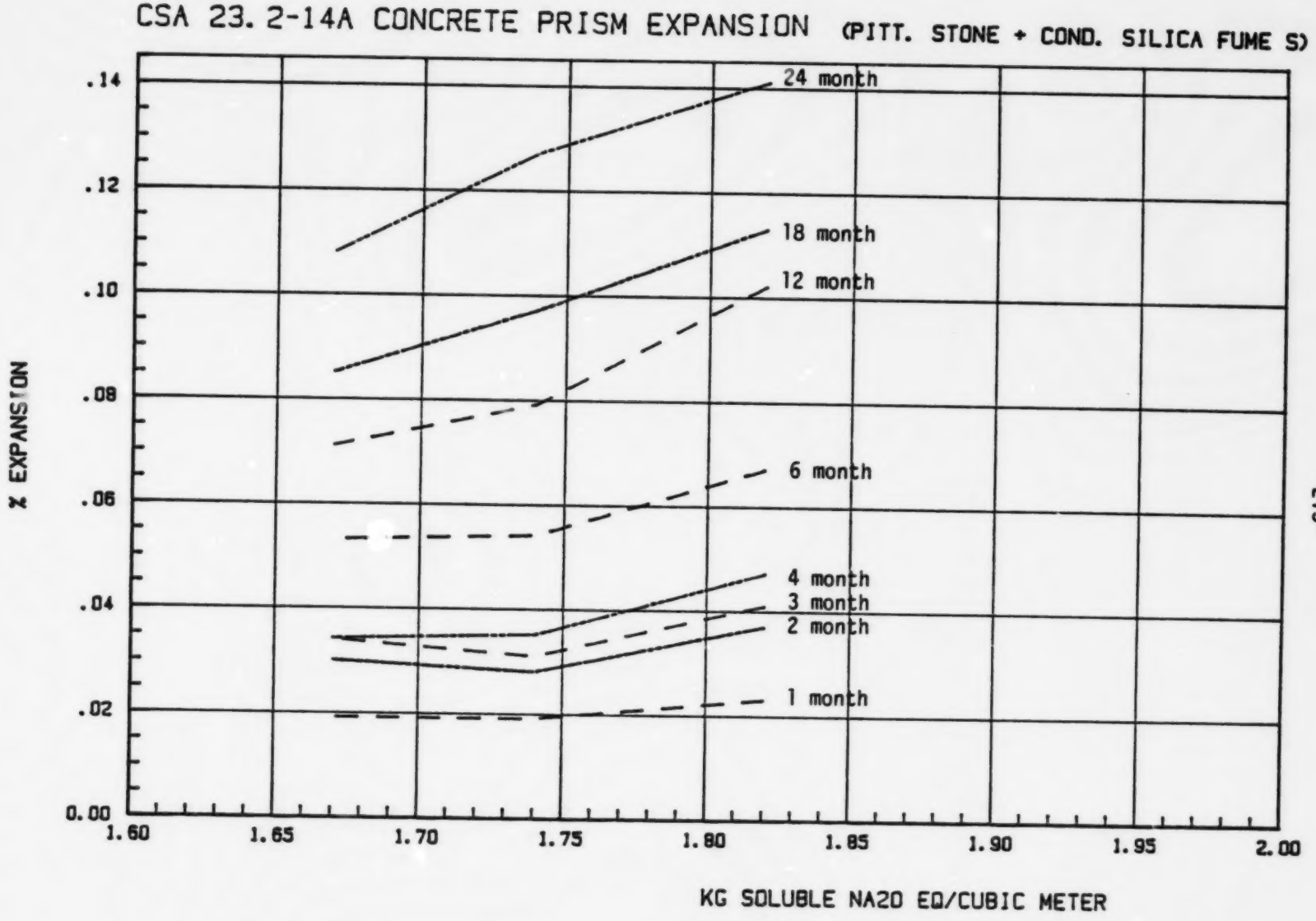

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME S)
% EXPANSION
.14
.12
.10
.08
.06
.04
.02
0.00
1.60
1.65
1.70
1.75
1.80
1.85
1.90
1.95
2.00
KG SOLUBLE NA2O EQ/CUBIC METER
24 month
18 month
12 month
6 month
4 month
3 month
2 month
1 month

Figure 129

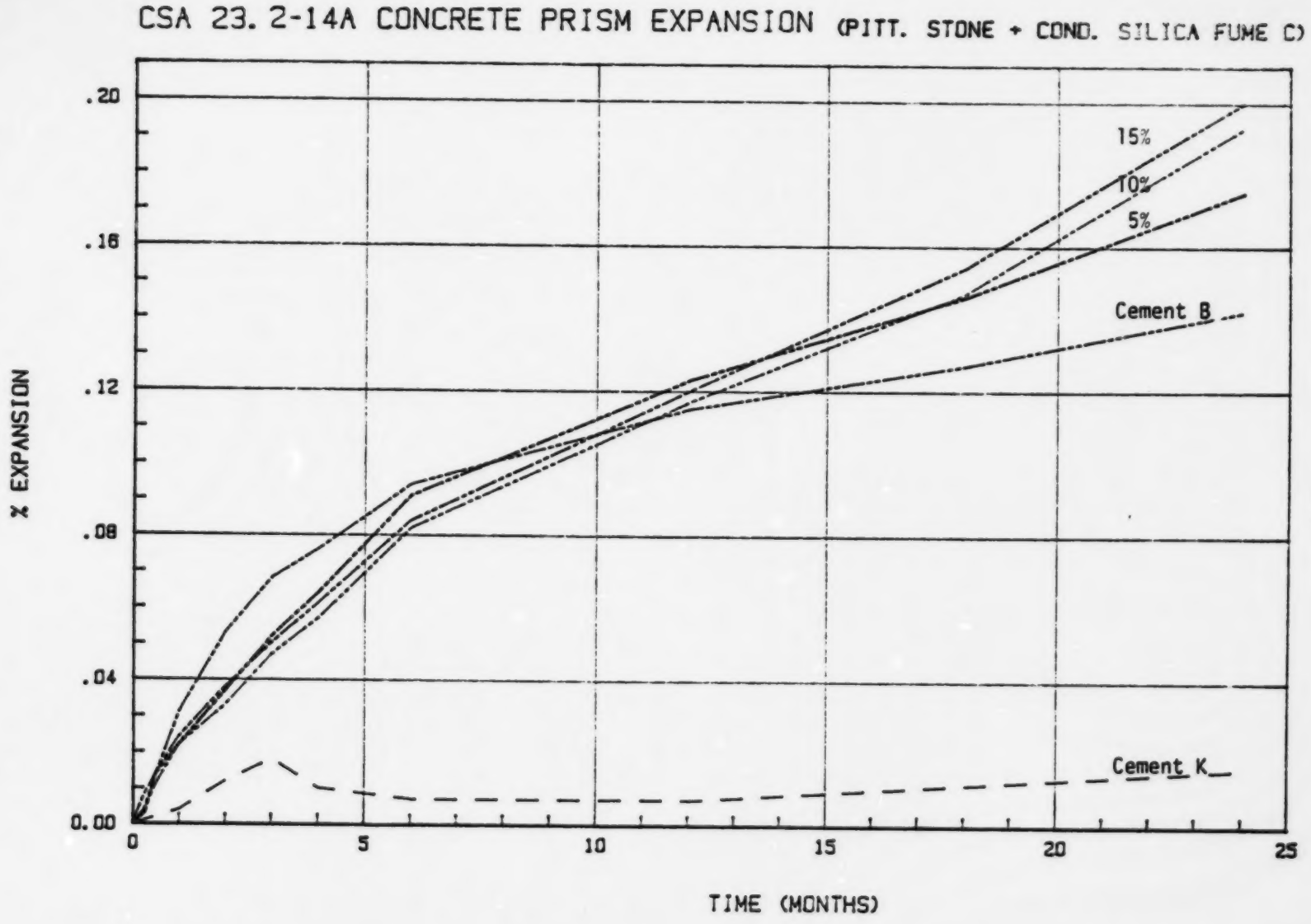

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME C)
.20
.16
.12
.08
.04
0.00
% EXPANSION
0
5
10
15
20
25
TIME (MONTHS)
15%
10%
5%
Cement B
Cement K

Figure 130

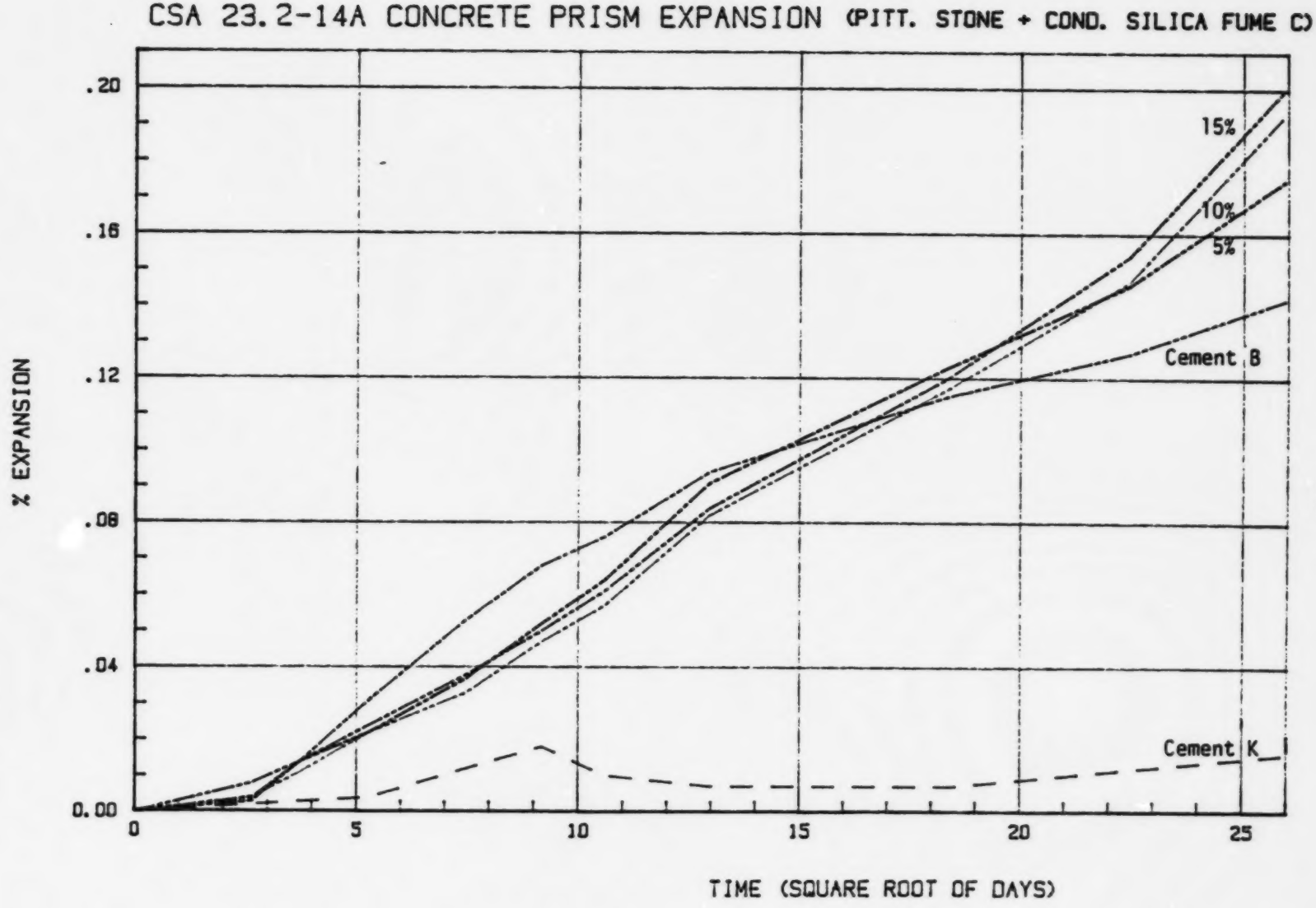

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME C)
% EXPANSION
.20
.16
.12
.08
.04
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
15%
10%
5%
Cement B
Cement K

Figure 131

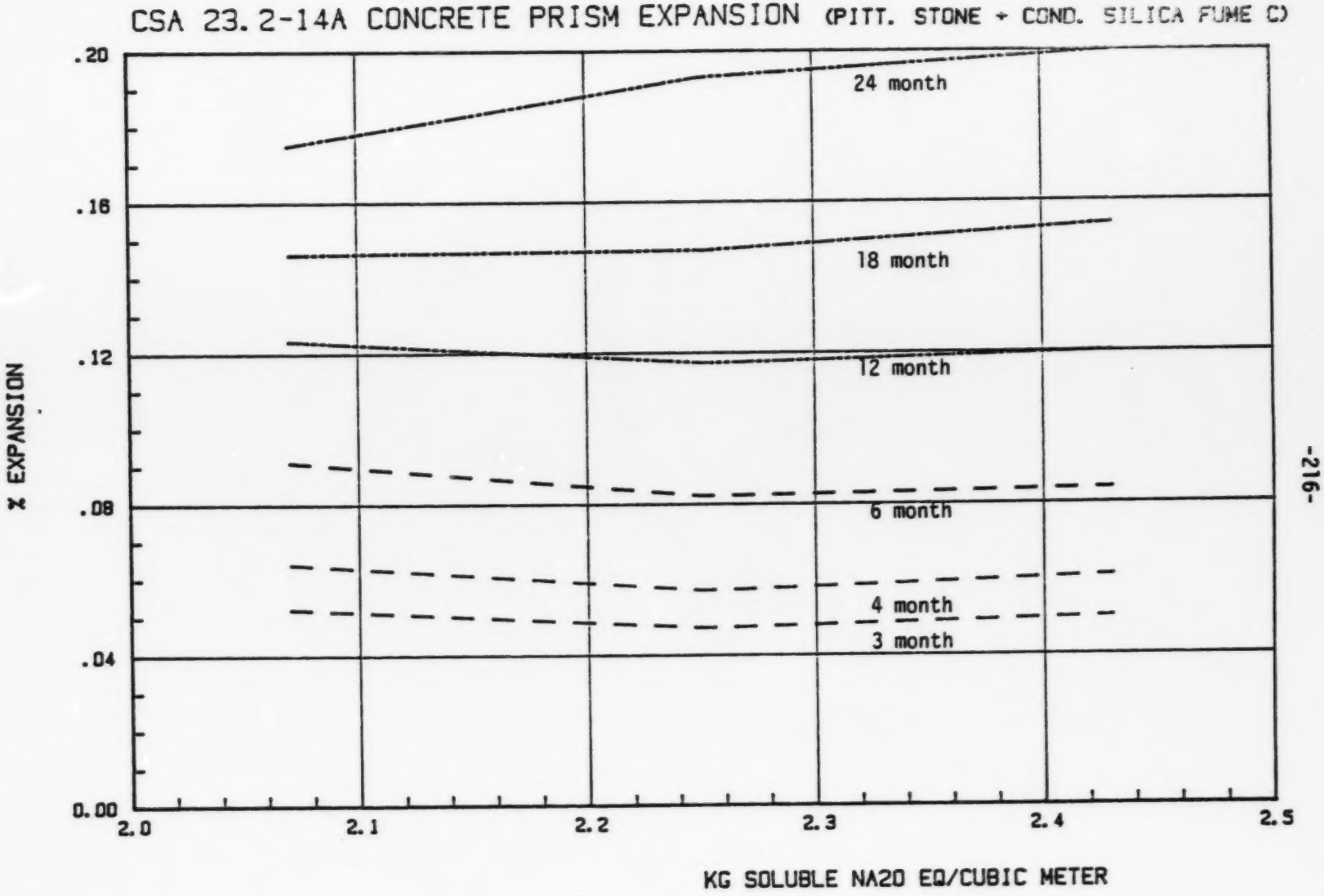

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + COND. SILICA FUME C)
.20
.16
.12
.08
.04
0.00
% EXPANSION
24 month
18 month
12 month
6 month
4 month
3 month
2.0
2.1
2.2
2.3
2.4
2.5
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 132

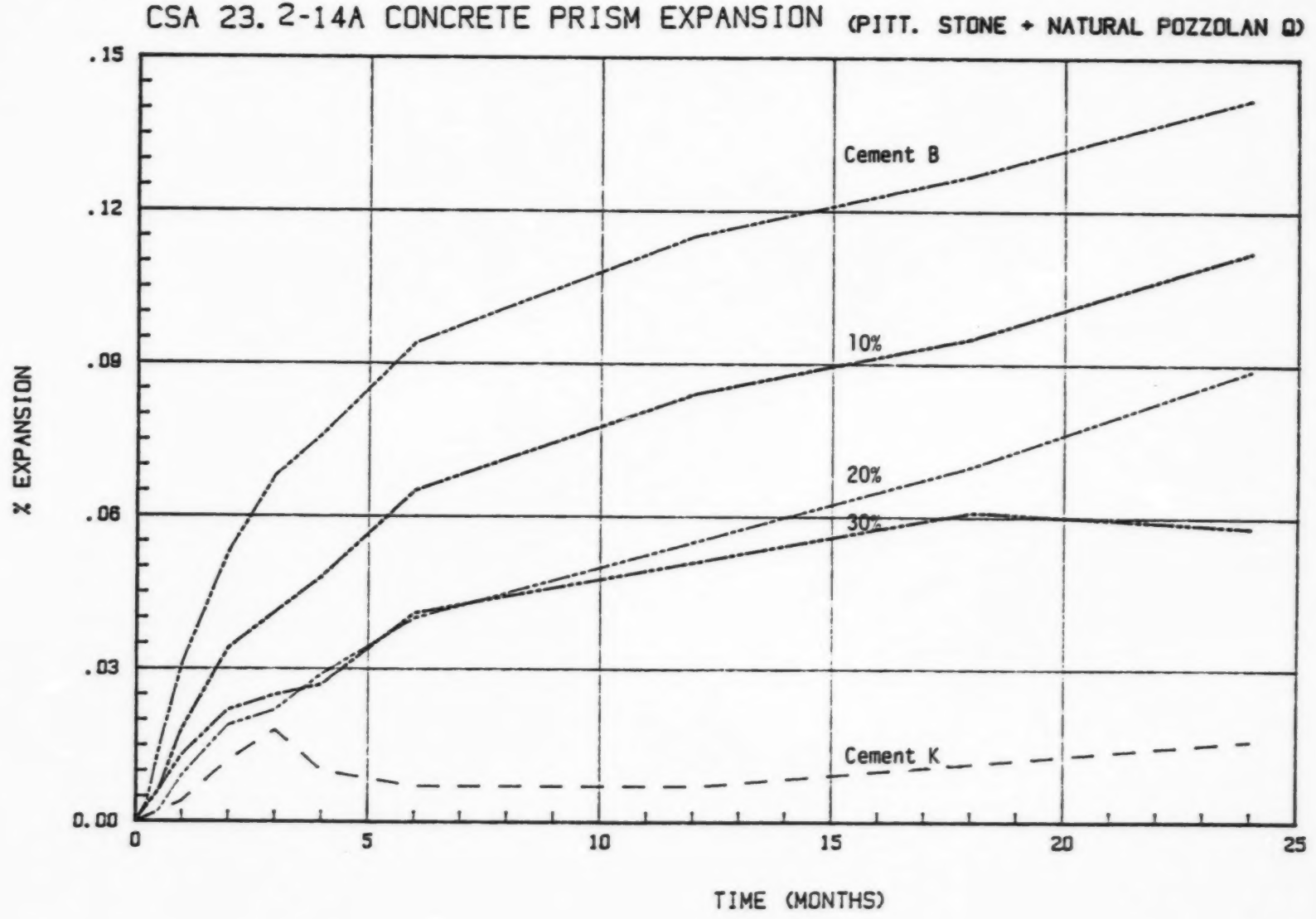

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN Q)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
30%
Cement K

Figure 133

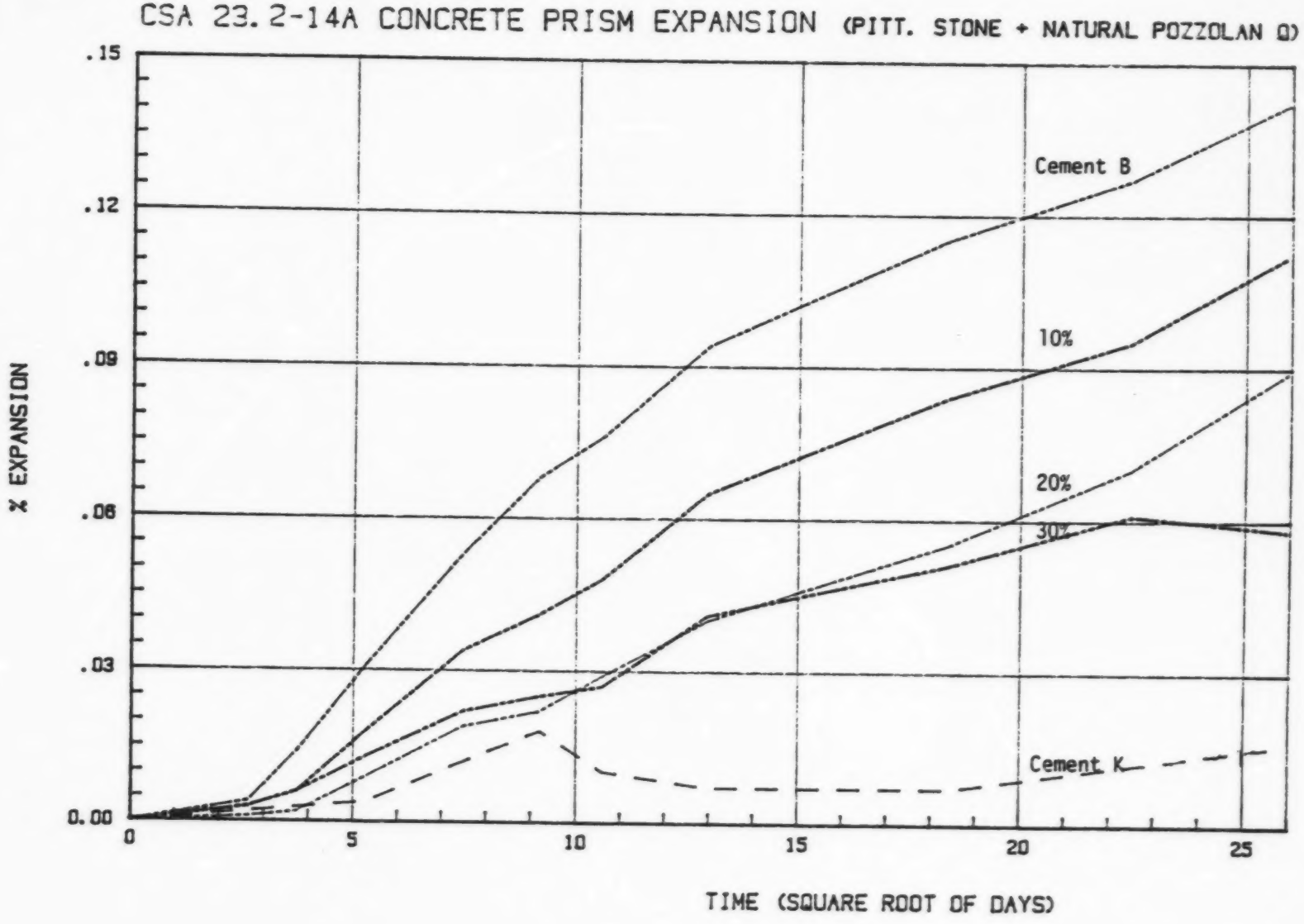

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN Q)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
Cement K

Figure 134

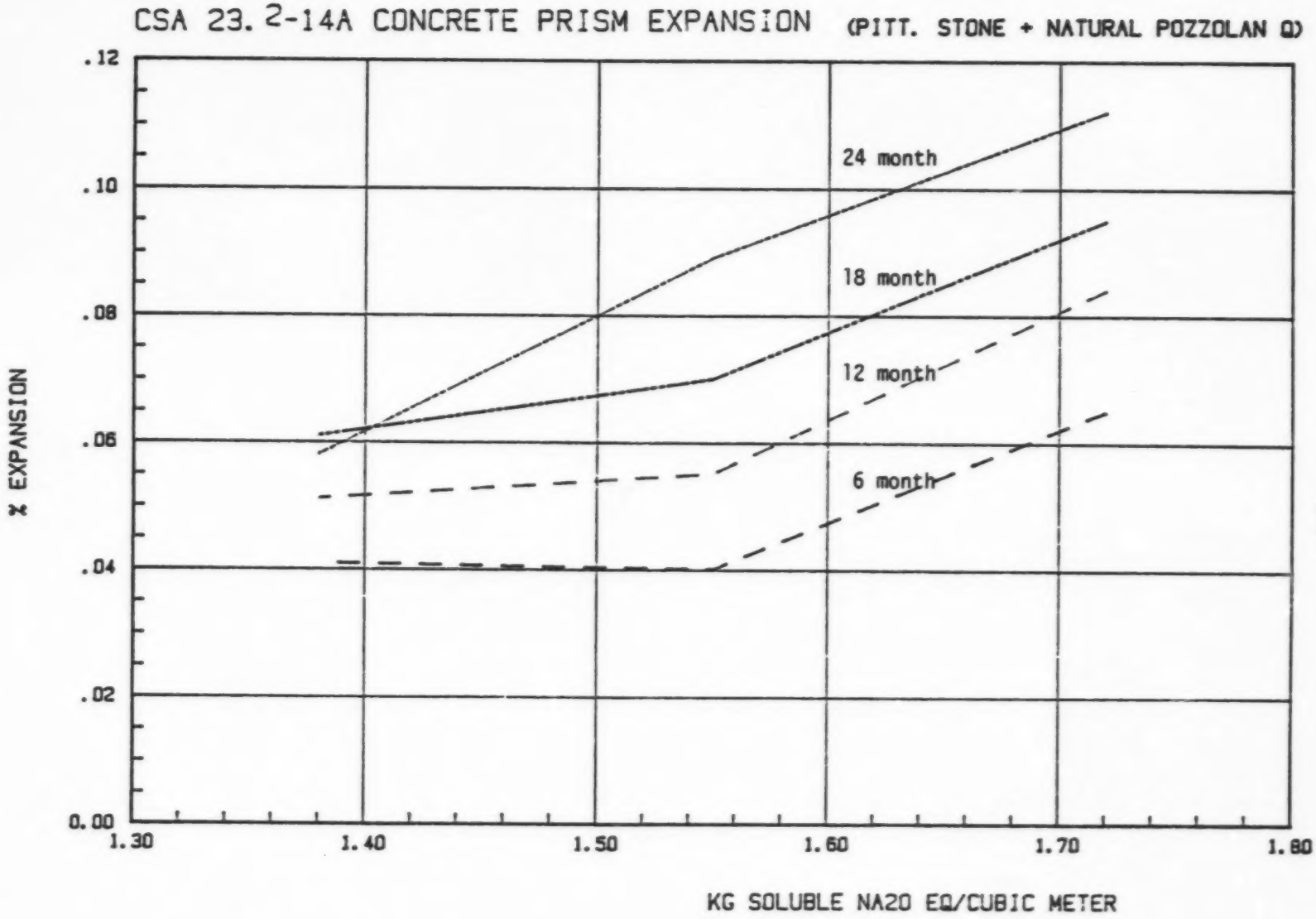

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN Q)
.12
.10
.08
.06
.04
.02
0.00
% EXPANSION
24 month
18 month
12 month
6 month
1.30
1.40
1.50
1.60
1.70
1.80
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 135

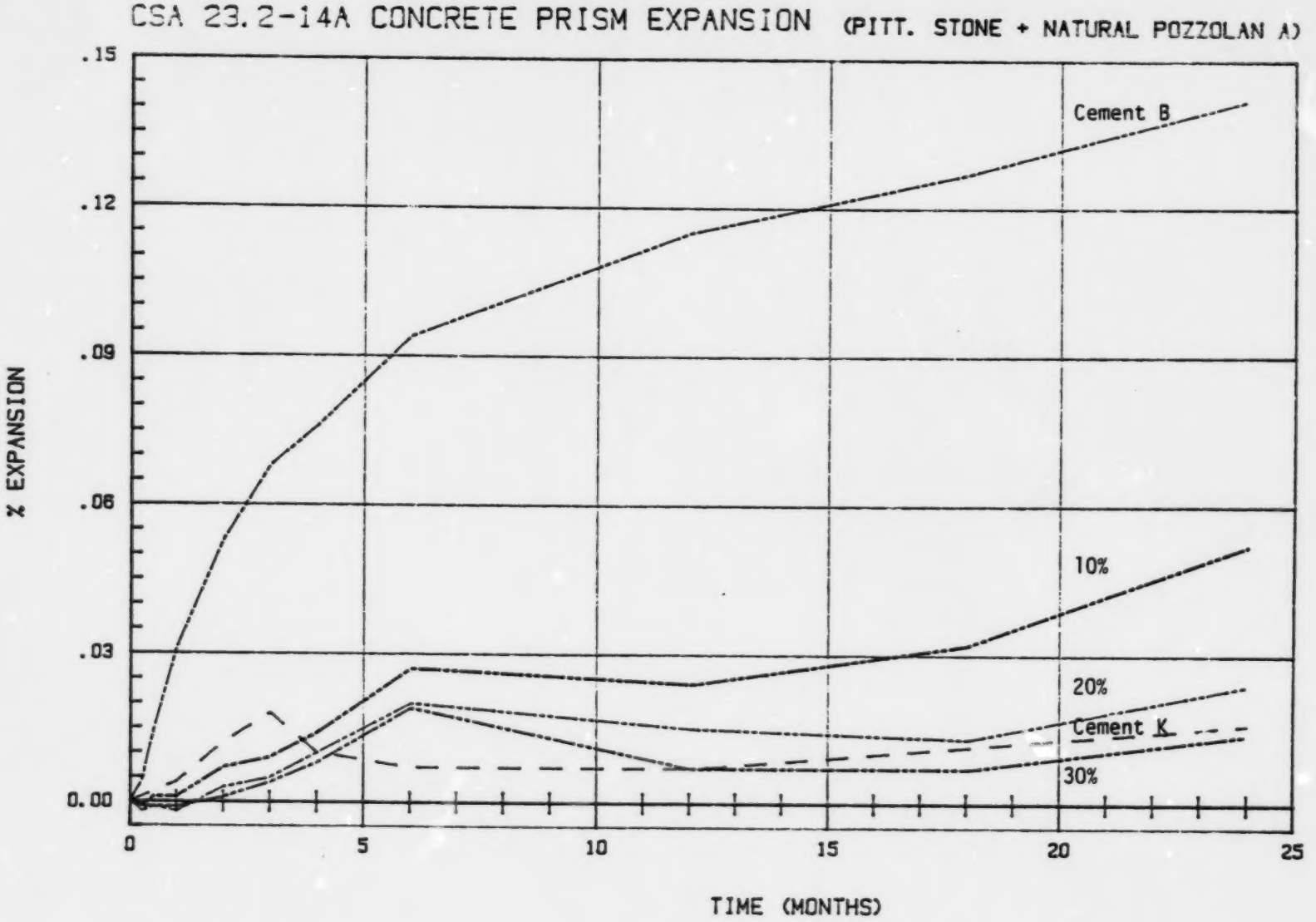

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN A)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (MONTHS)
Cement B
10%
20%
Cement K
30%

Figure 136

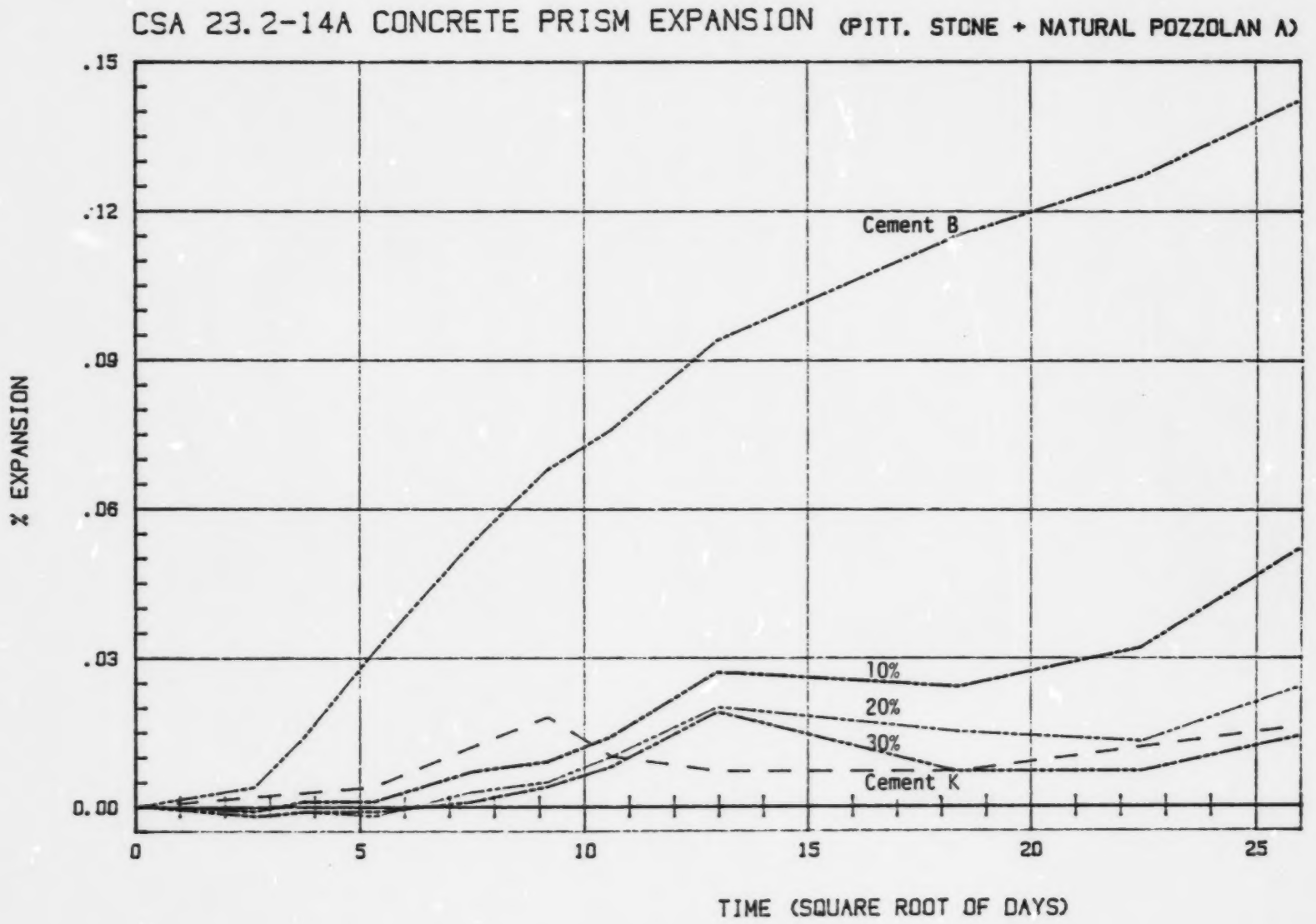

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN A)
% EXPANSION
.15
.12
.09
.06
.03
0.00
0
5
10
15
20
25
TIME (SQUARE ROOT OF DAYS)
Cement B
10%
20%
30%
Cement K

Figure 137

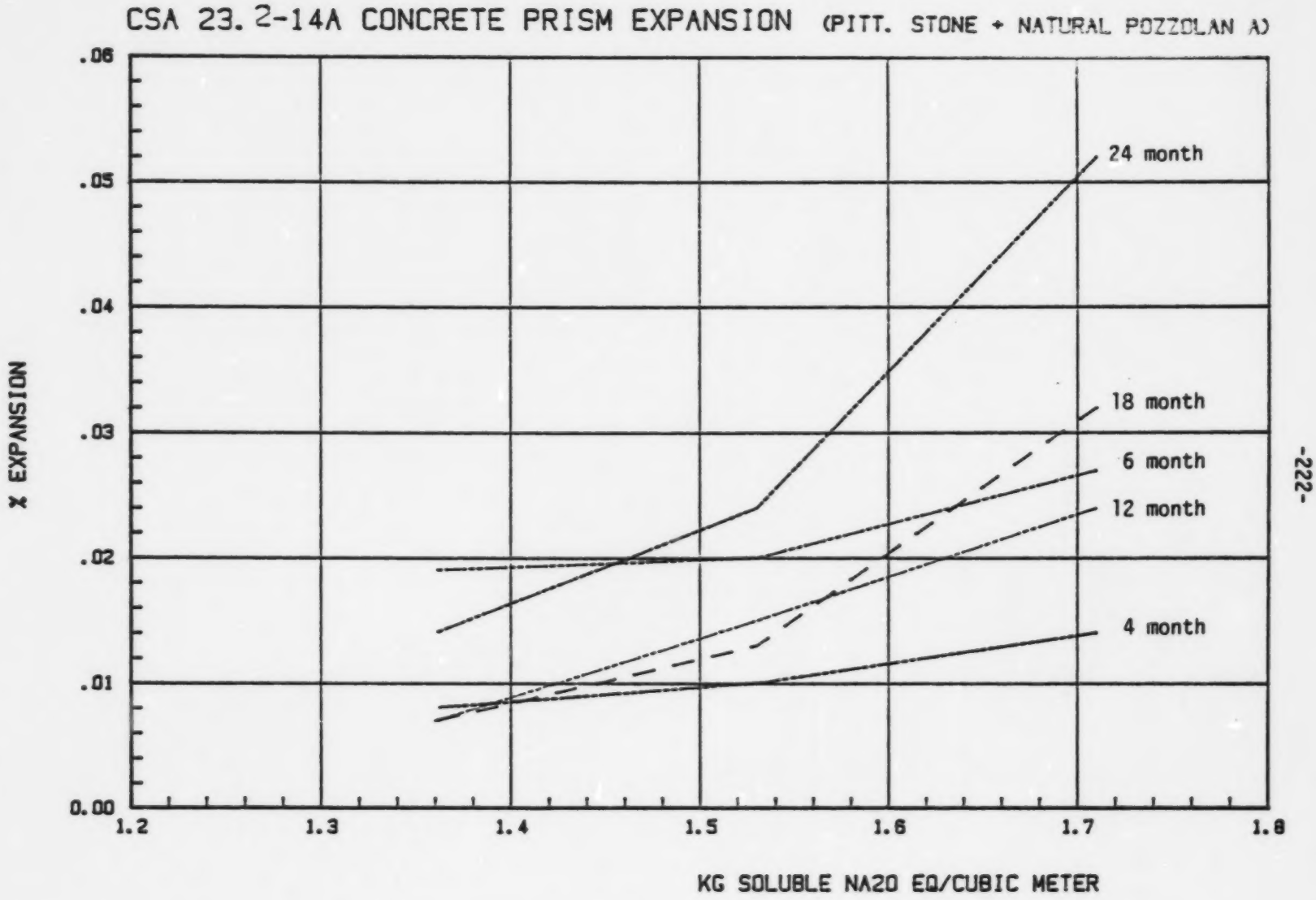
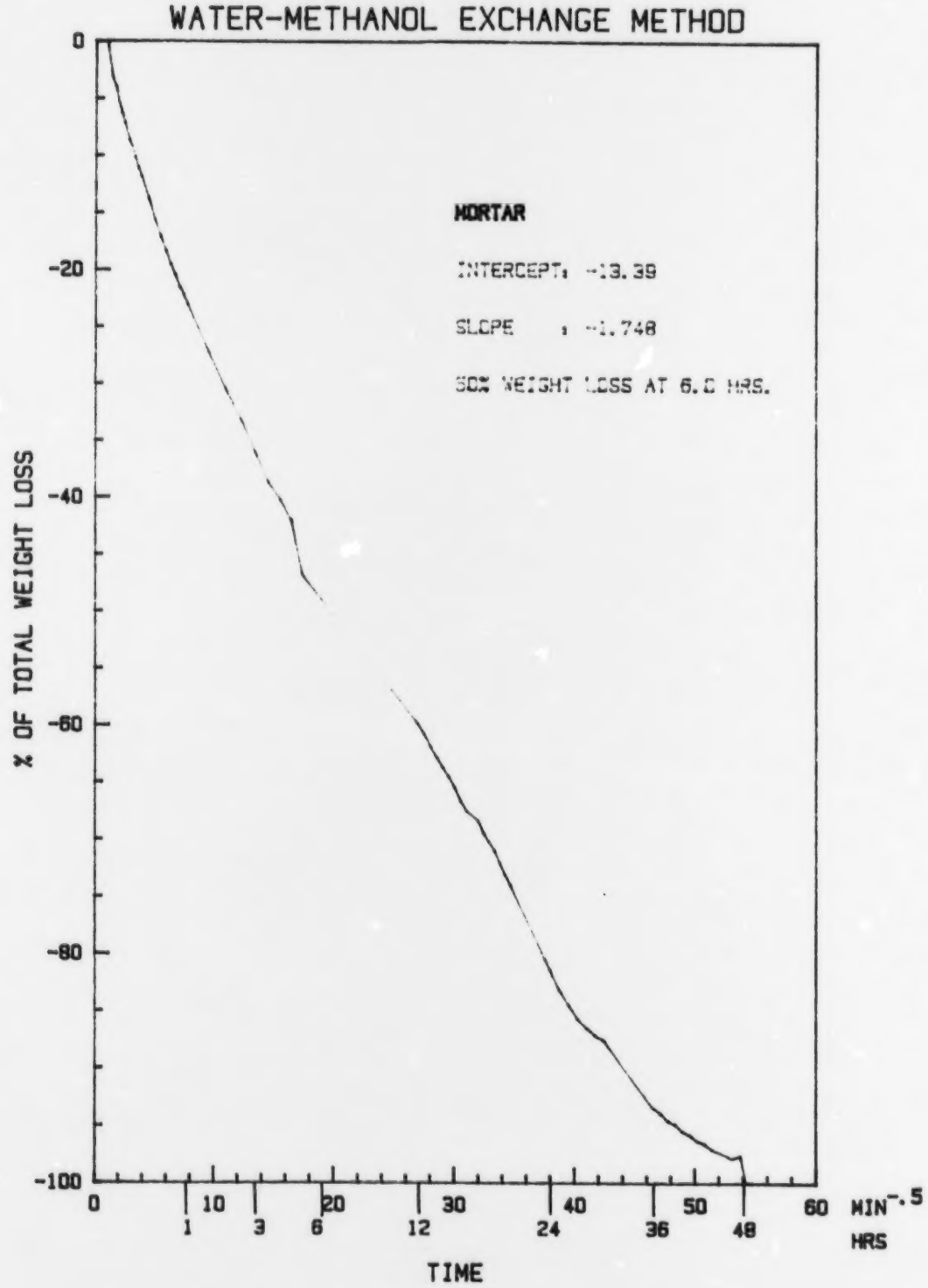
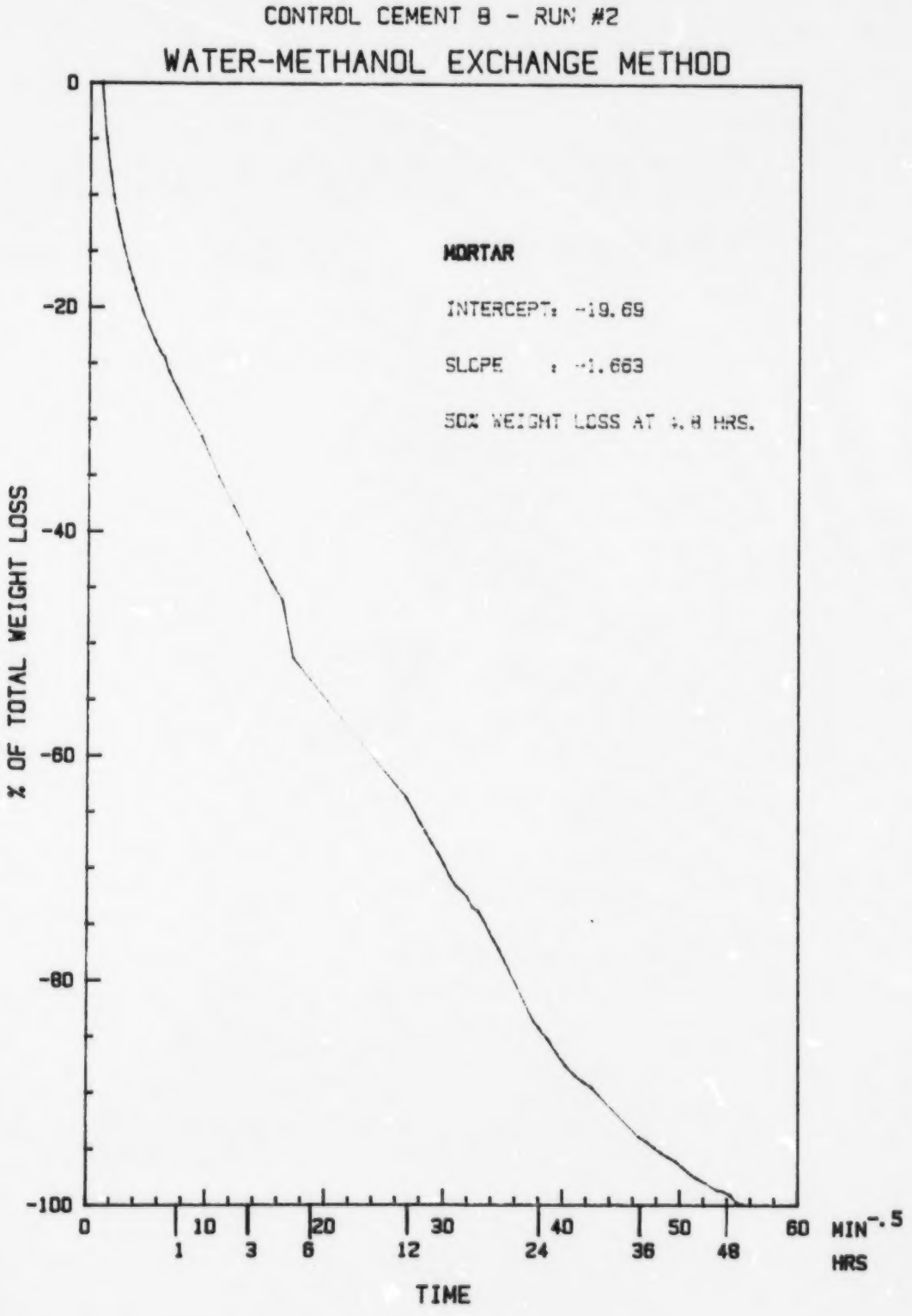

CSA 23.2-14A CONCRETE PRISM EXPANSION (PITT. STONE + NATURAL POZZOLAN A)
% EXPANSION
.06
.05
.04
.03
.02
.01
0.00
1.2
1.3
1.4
1.5
1.6
1.7
1.8
24 month
18 month
6 month
12 month
4 month
KG SOLUBLE NA2O EQ/CUBIC METER

Figure 138

CONTROL CEMENT B - RUN #1

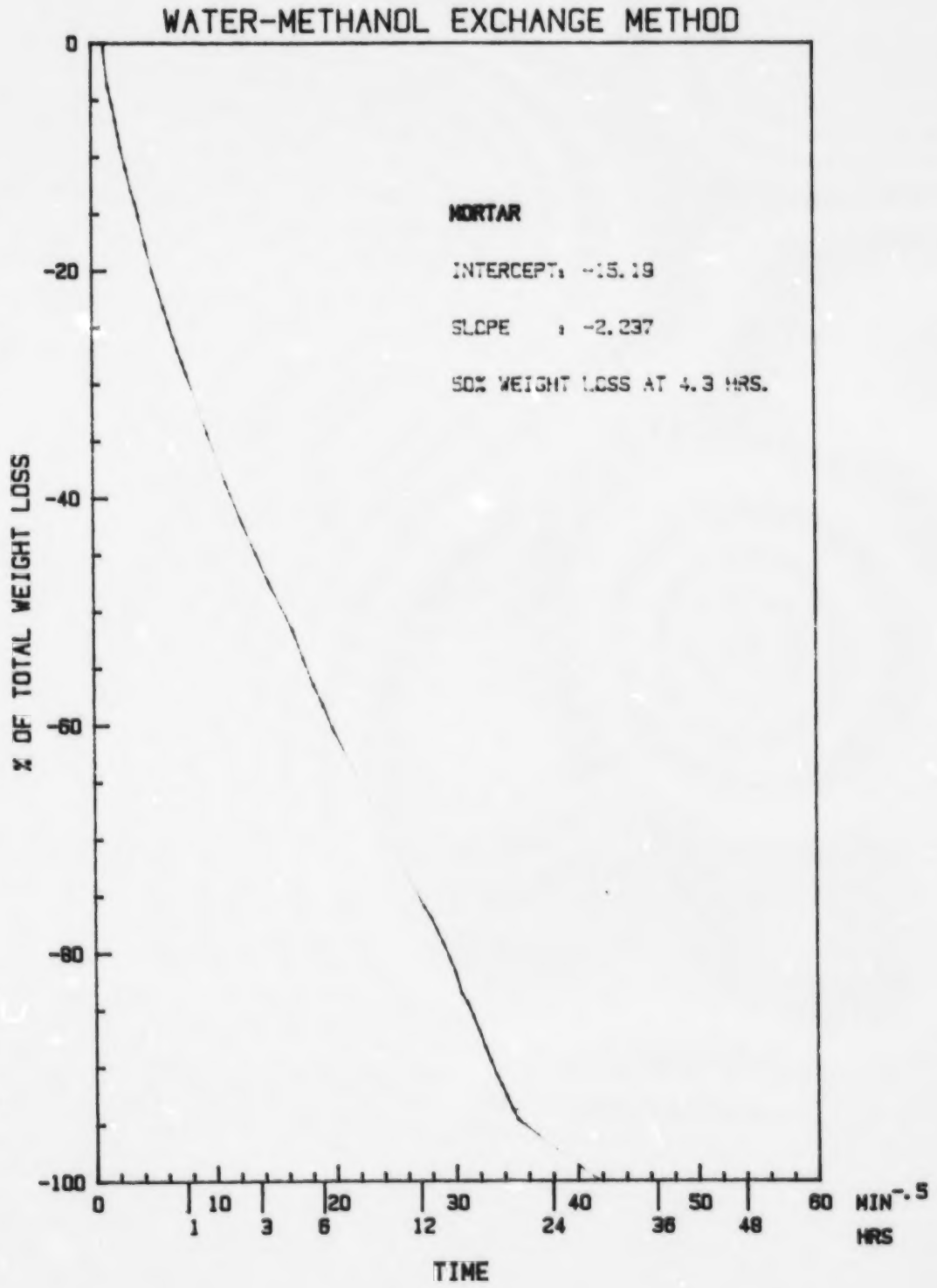


Appendix A-1

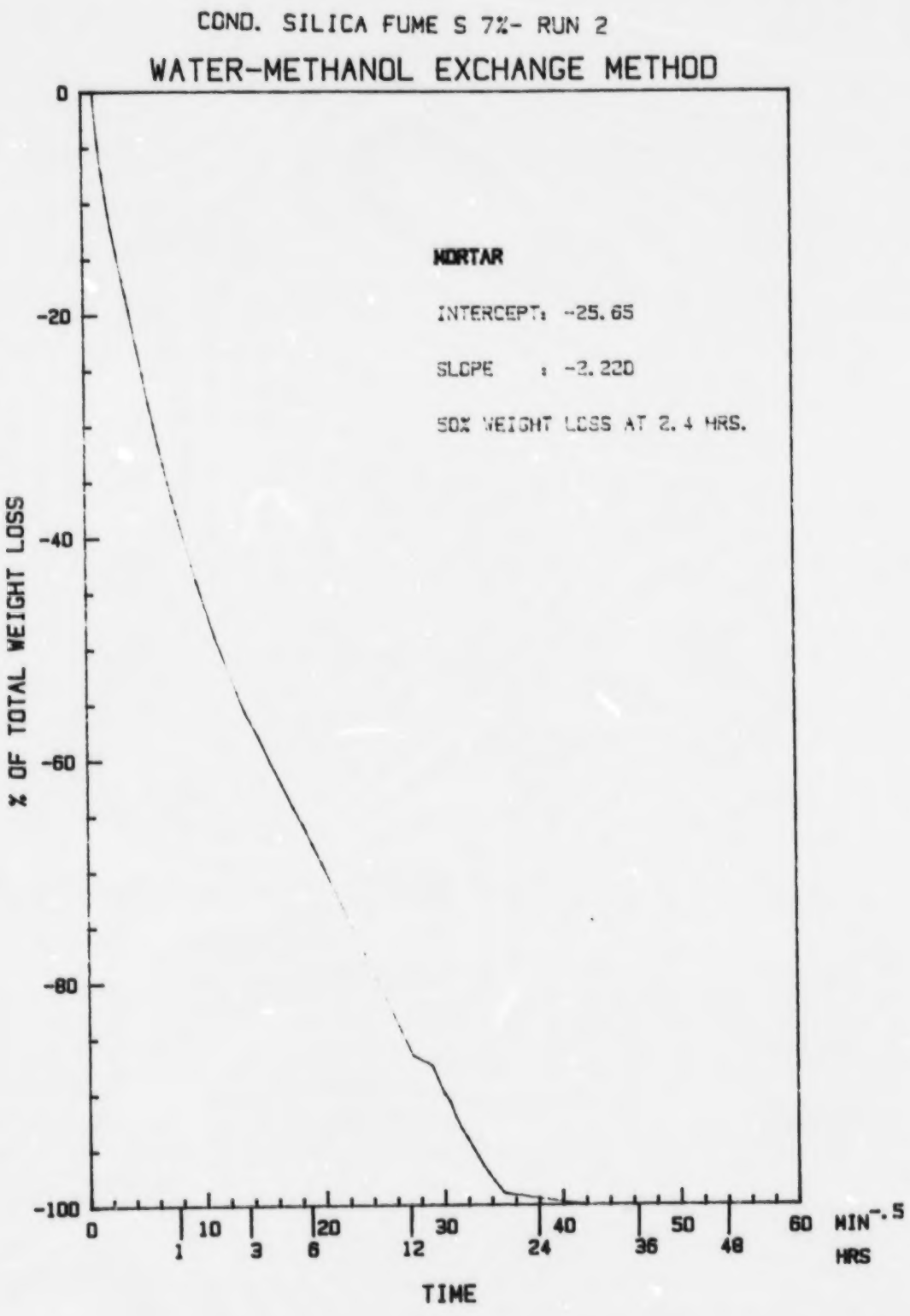

CONTROL CEMENT B - RUN #2
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -19.69
SLOPE : -1.663
50% WEIGHT LOSS AT 4.8 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
MIN^-.5
1
3
6
12
24
36
48
HRS
TIME

Appendix A-2

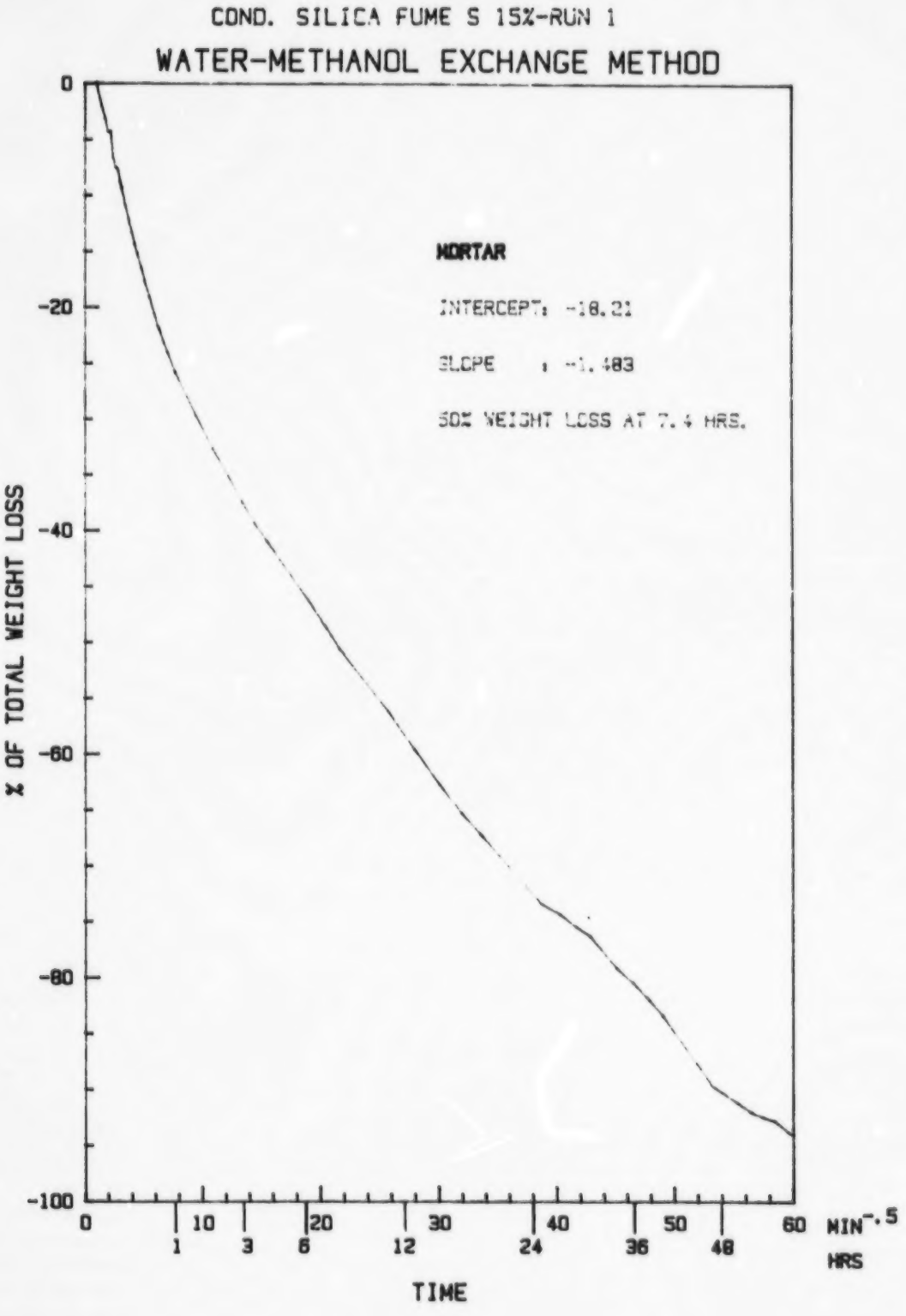
CONO. SILICA FUME S 7%- RUN #1



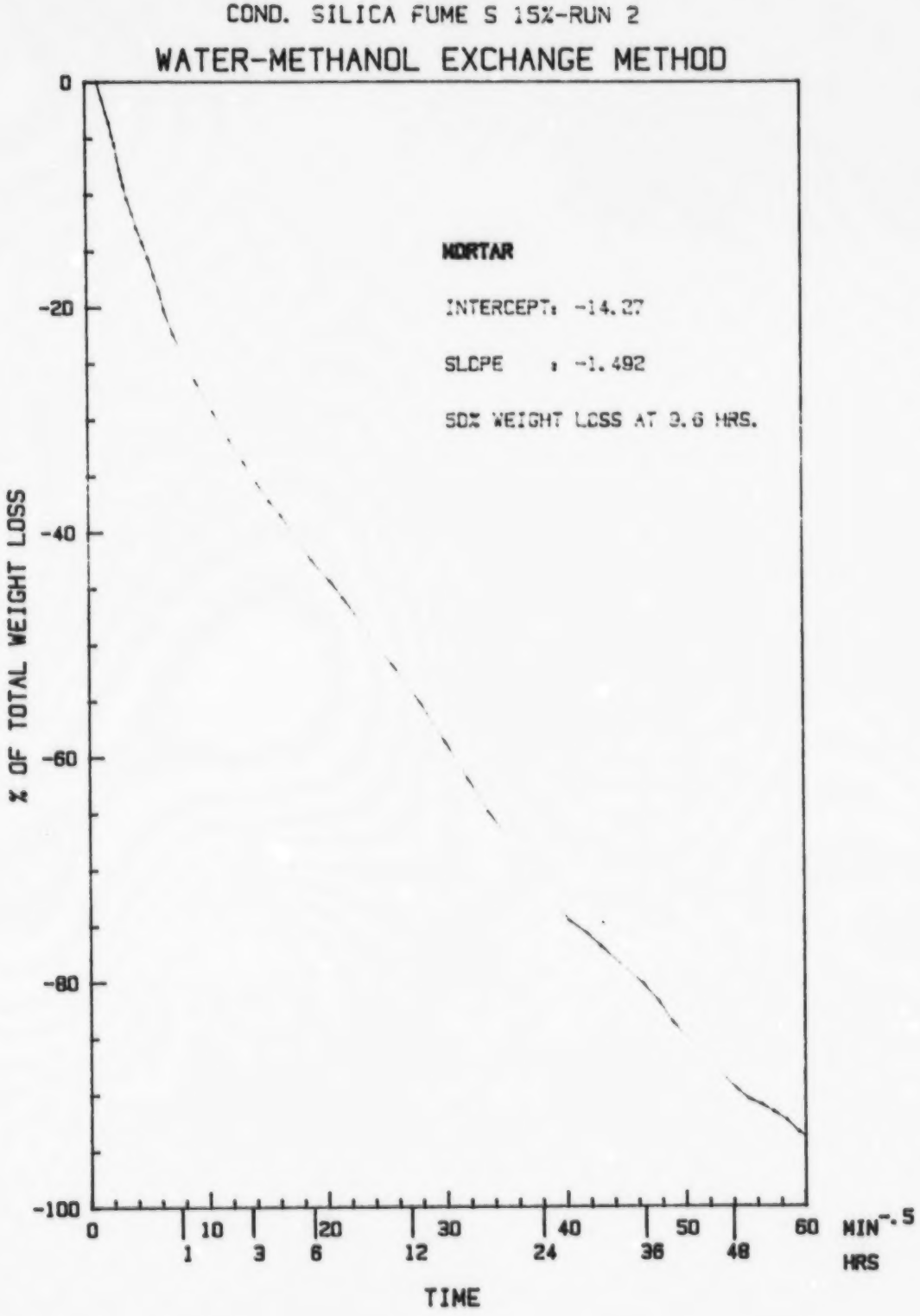
Appendix A-3


COND. SILICA FUME S 7%- RUN 2
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -25.65
SLOPE : -2.220
50% WEIGHT LOSS AT 2.4 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
MIN^-.5
1
3
6
12
24
36
48
HRS
TIME

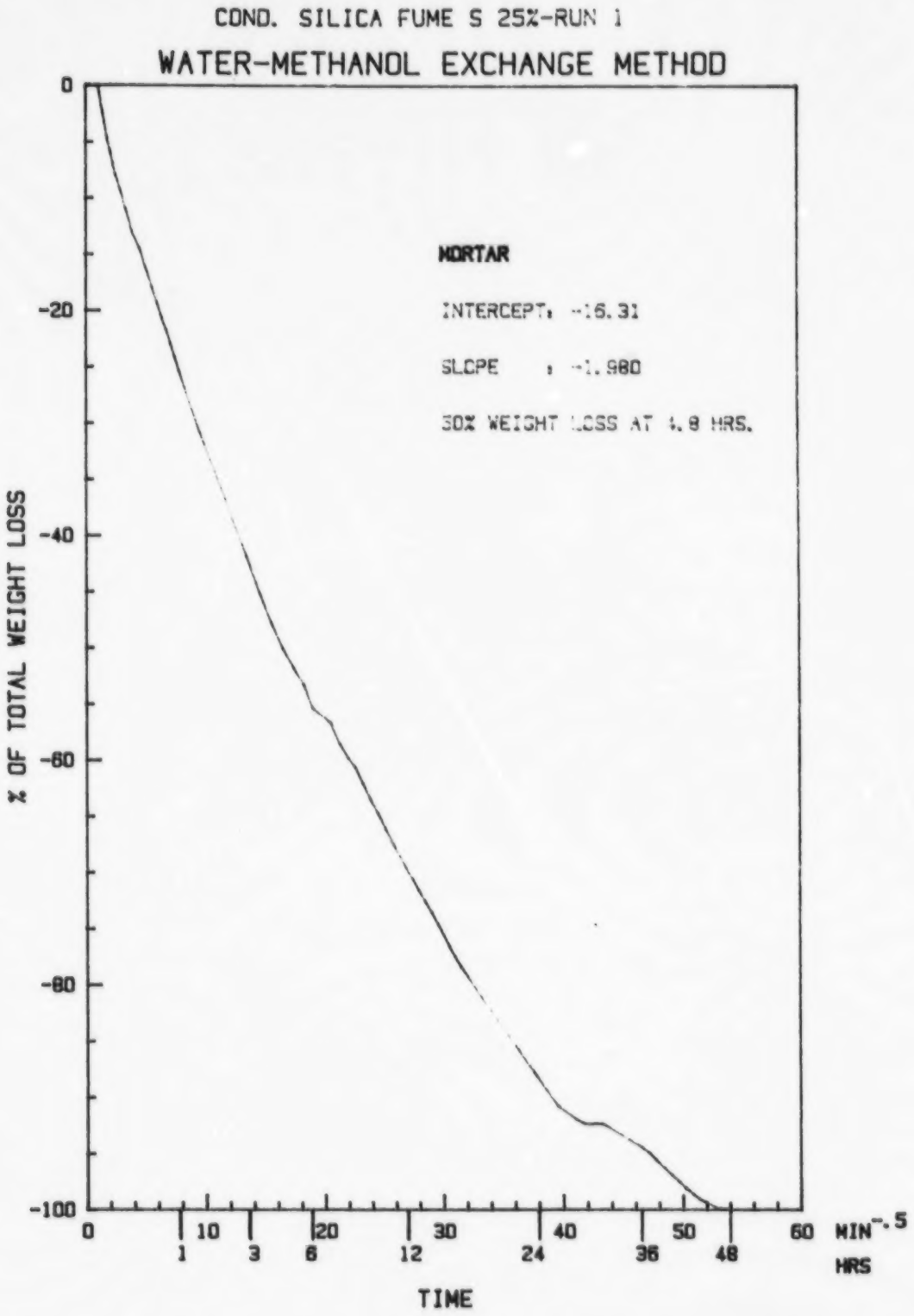
Appendix A-4


COND. SILICA FUME S 15%-RUN 1
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -18.21
SLOPE : -1.483
50% WEIGHT LOSS AT 7.4 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
1
10
3
20
6
30
12
40
24
50
36
60
48
MIN^.5
HRS
TIME

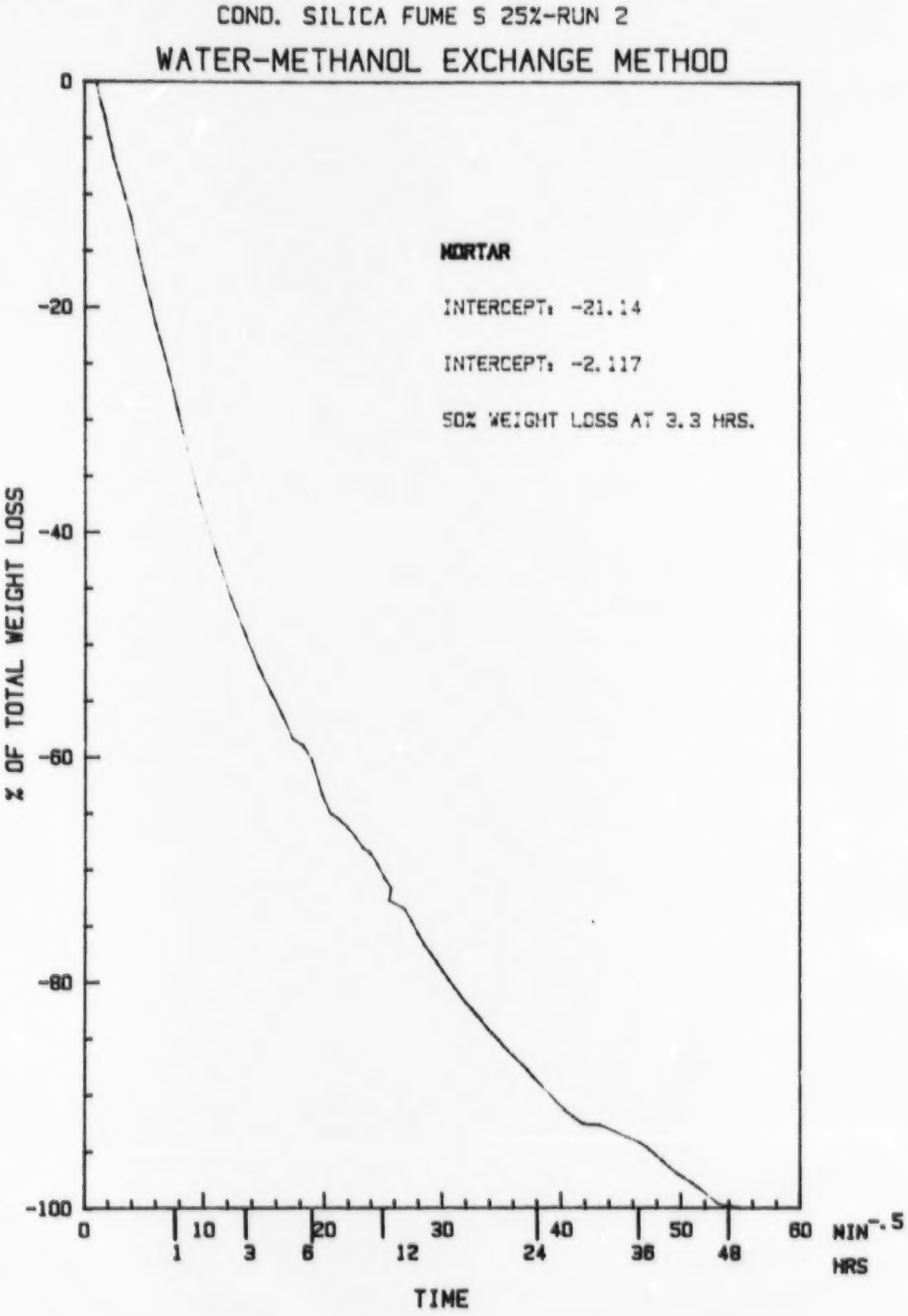
Appendix A-5


COND. SILICA FUME S 15%-RUN 2
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -14.27
SLOPE : -1.492
50% WEIGHT LOSS AT 3.6 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
MIN^-.5
1
3
6
12
24
36
48
HRS
TIME

Appendix A-6

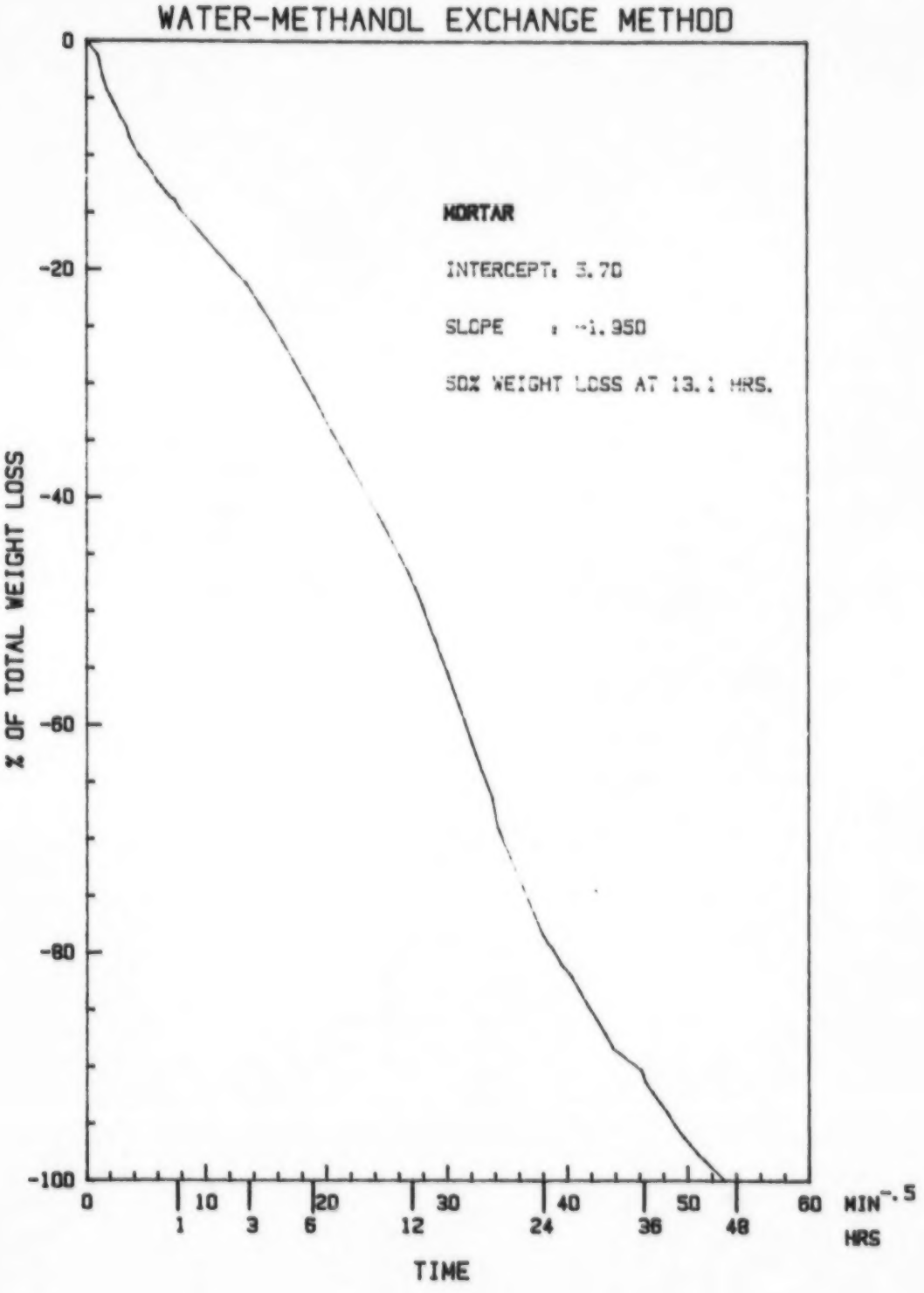

COND. SILICA FUME S 25%-RUN 1
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -16.31
SLOPE : -1.980
30% WEIGHT LOSS AT 4.8 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
MIN^-.5
1
3
6
12
24
36
48
HRS
TIME

Appendix A-7

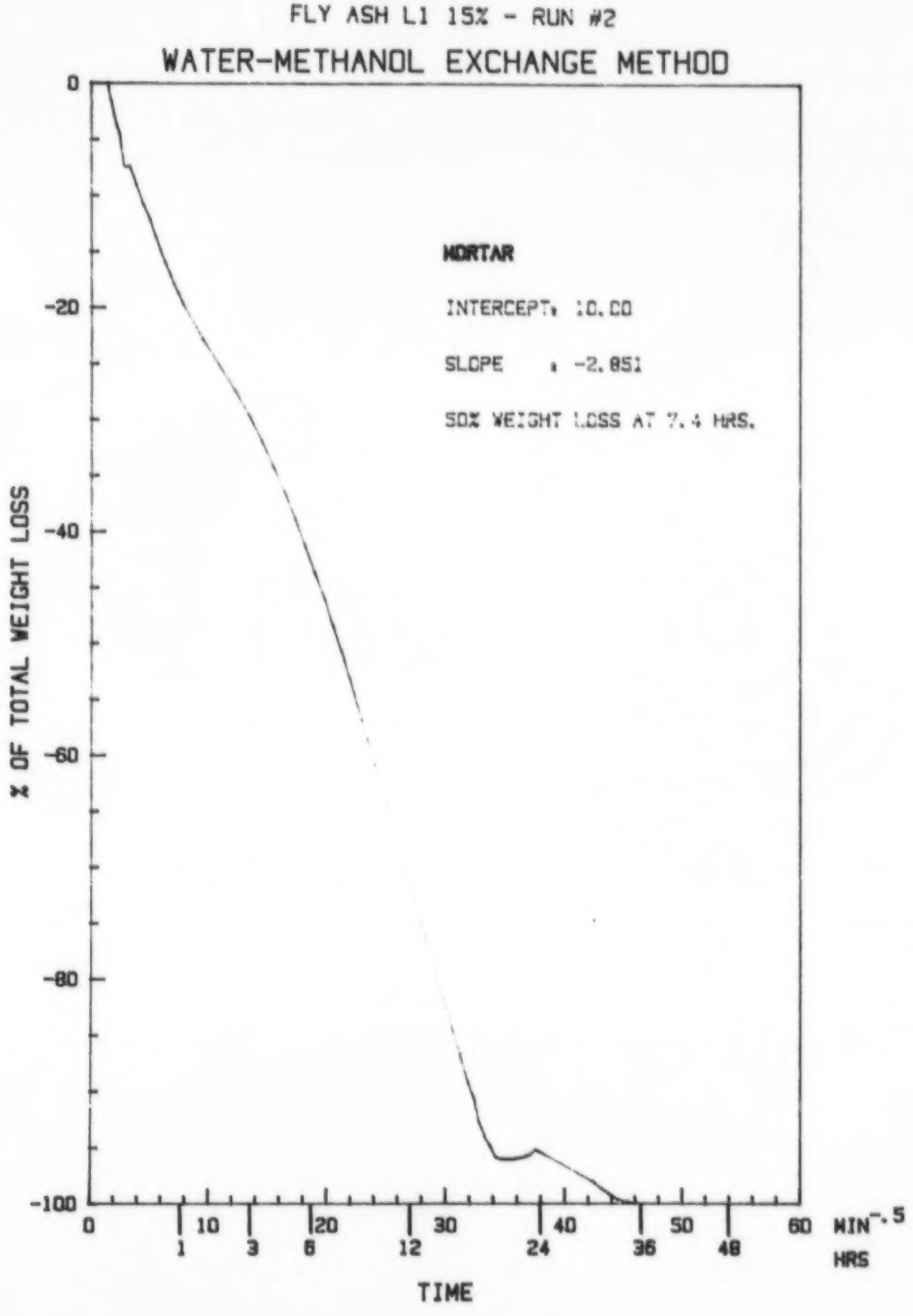

COND. SILICA FUME S 25%-RUN 2
WATER-METHANOL EXCHANGE METHOD
MORTAR
INTERCEPT: -21.14
INTERCEPT: -2.117
50% WEIGHT LOSS AT 3.3 HRS.
% OF TOTAL WEIGHT LOSS
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
MIN^-.5
1
3
6
12
24
36
48
HRS
TIME

Appendix A-8

FLY ASH L1 15% - RUN #1

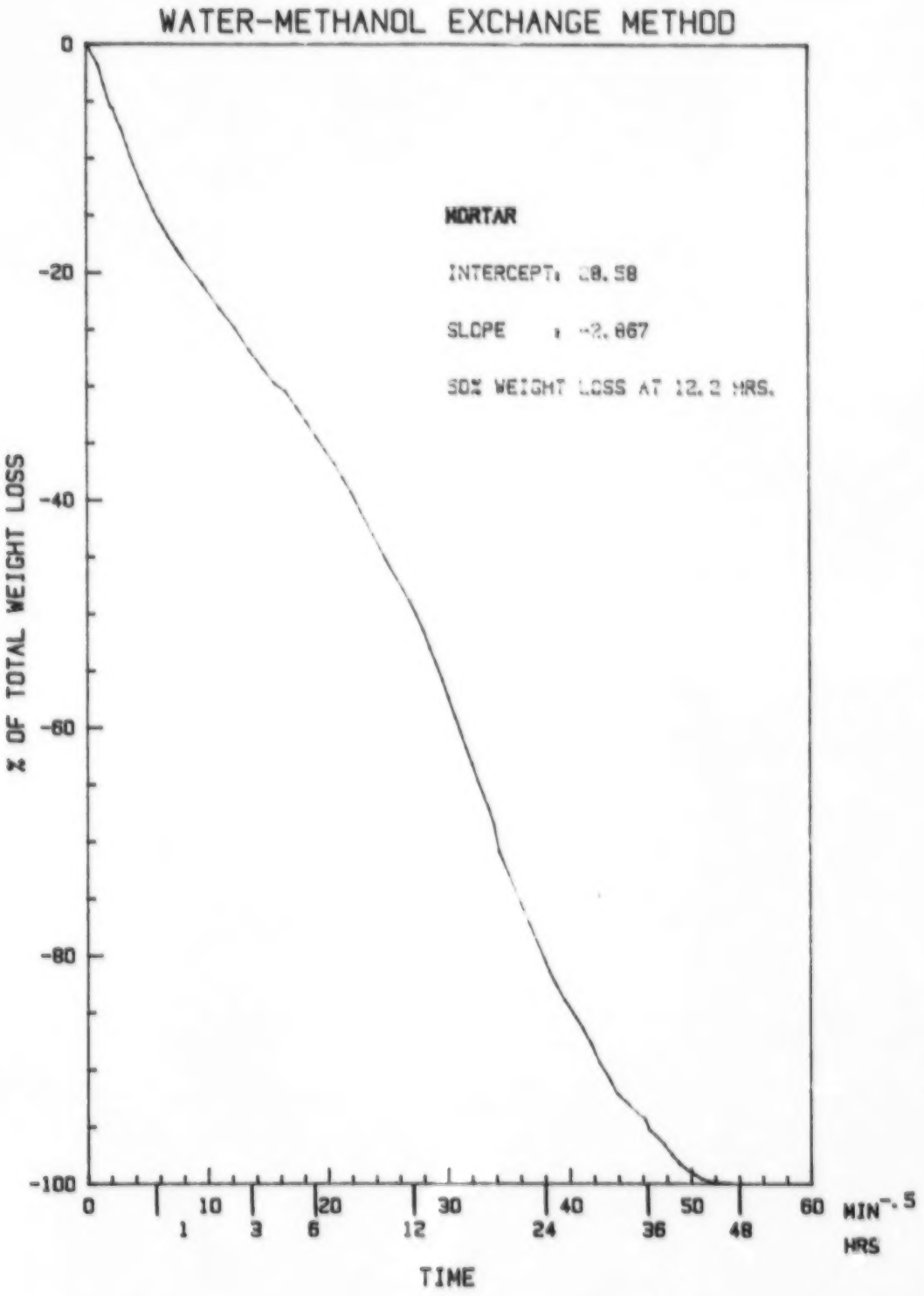


Appendix A-9

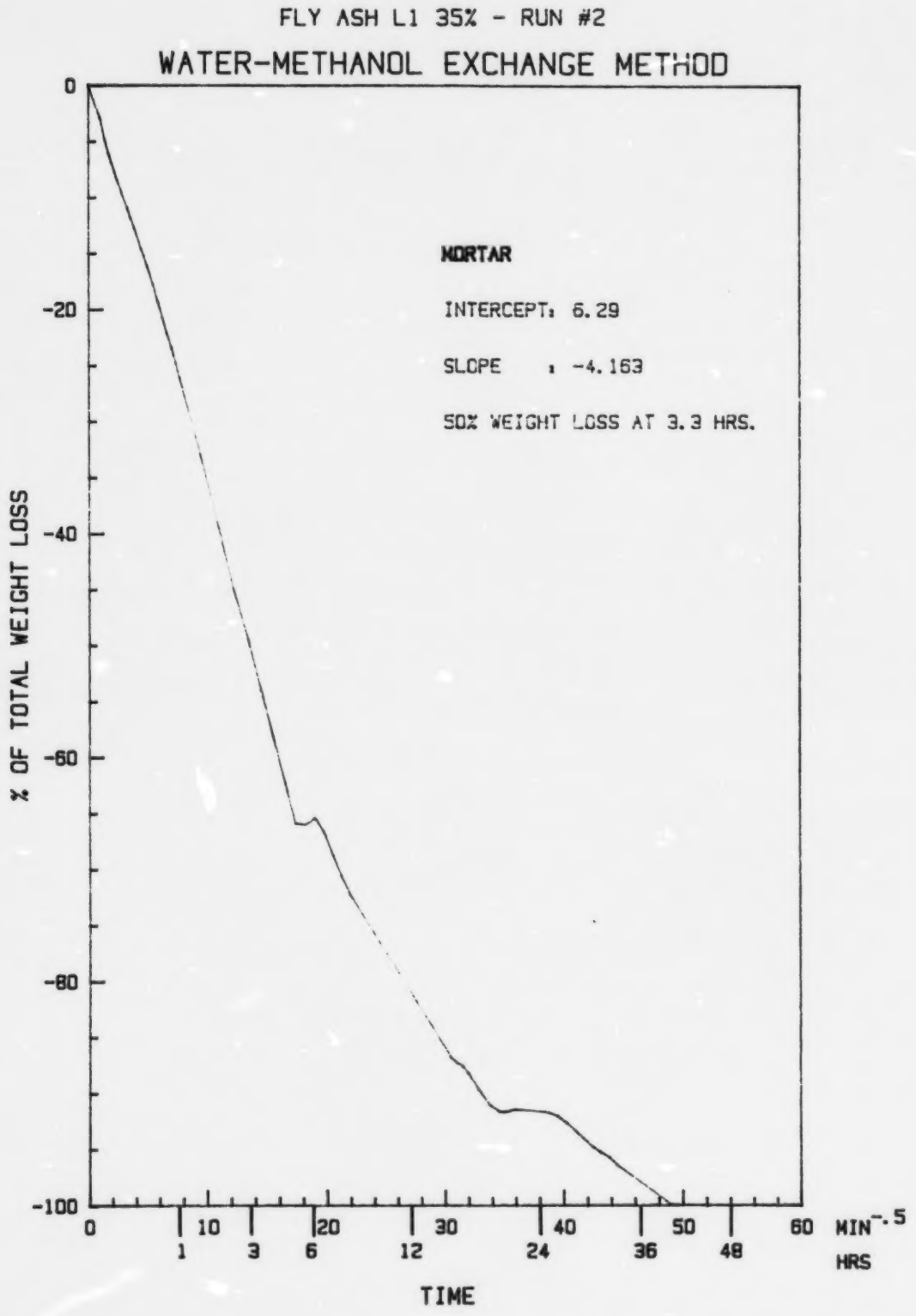


Appendix A-10

FLY ASH L1 25% - RUN #2

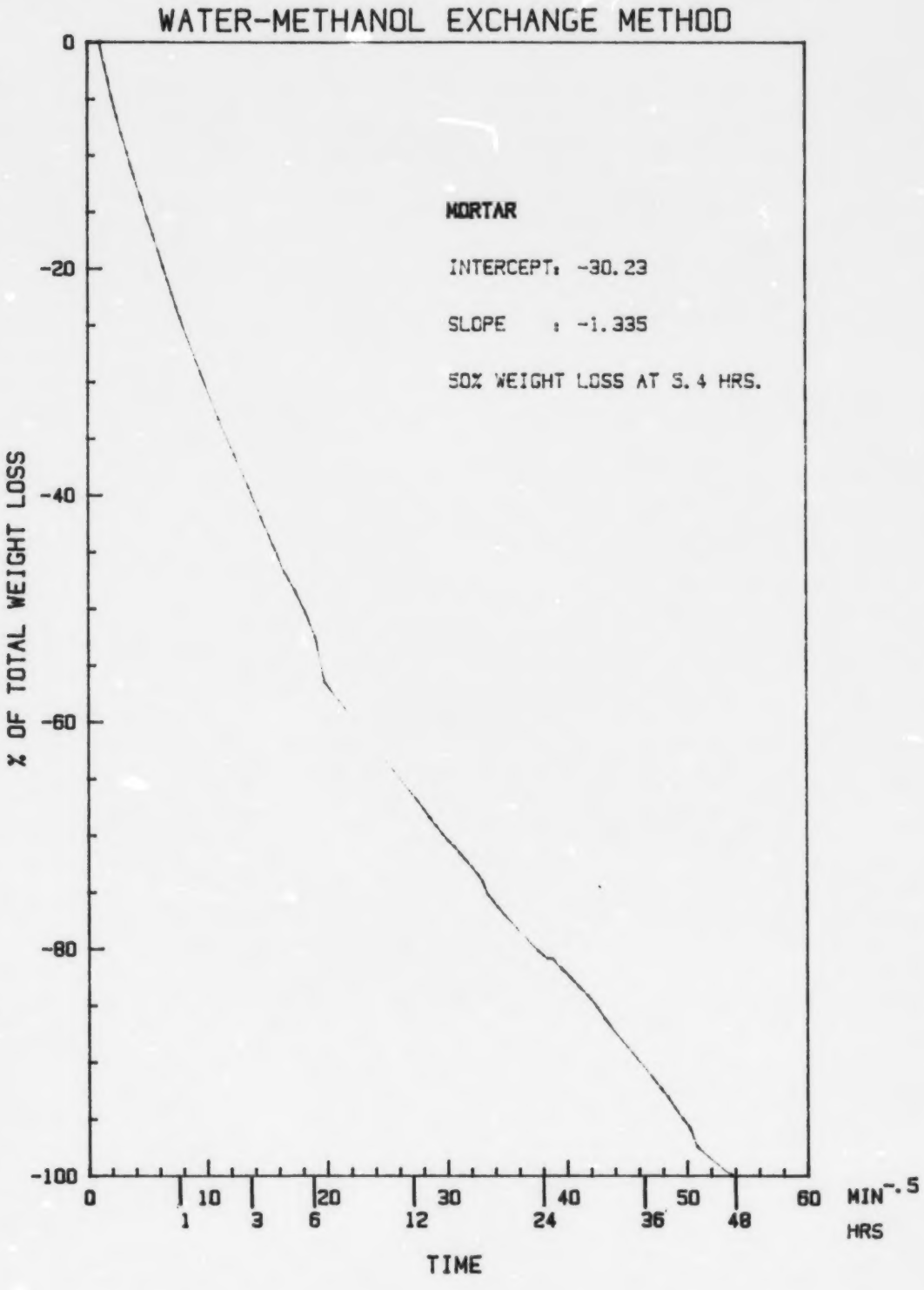


Appendix A-11

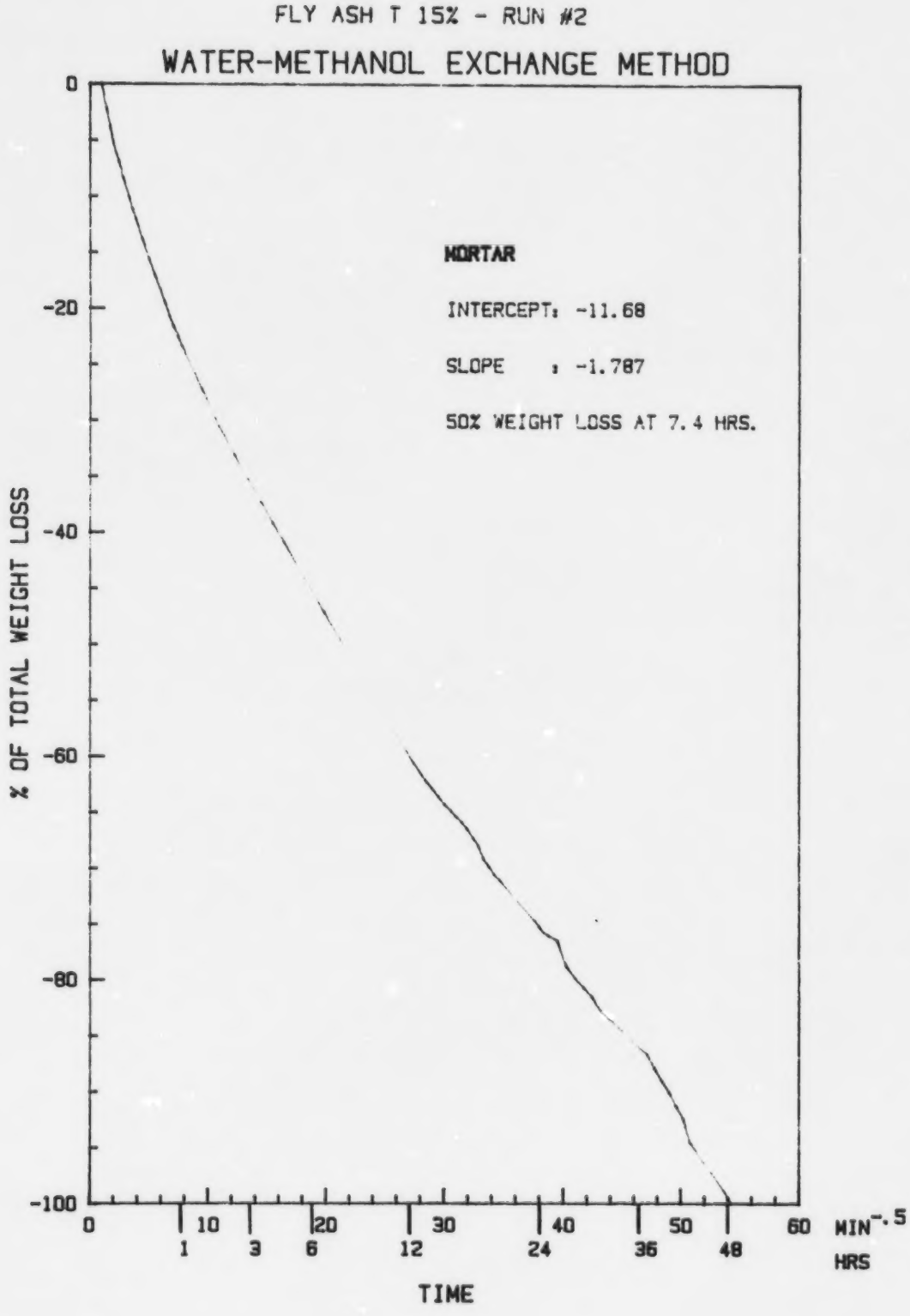


Appendix A-12

FLY ASH T 15% - RUN #1

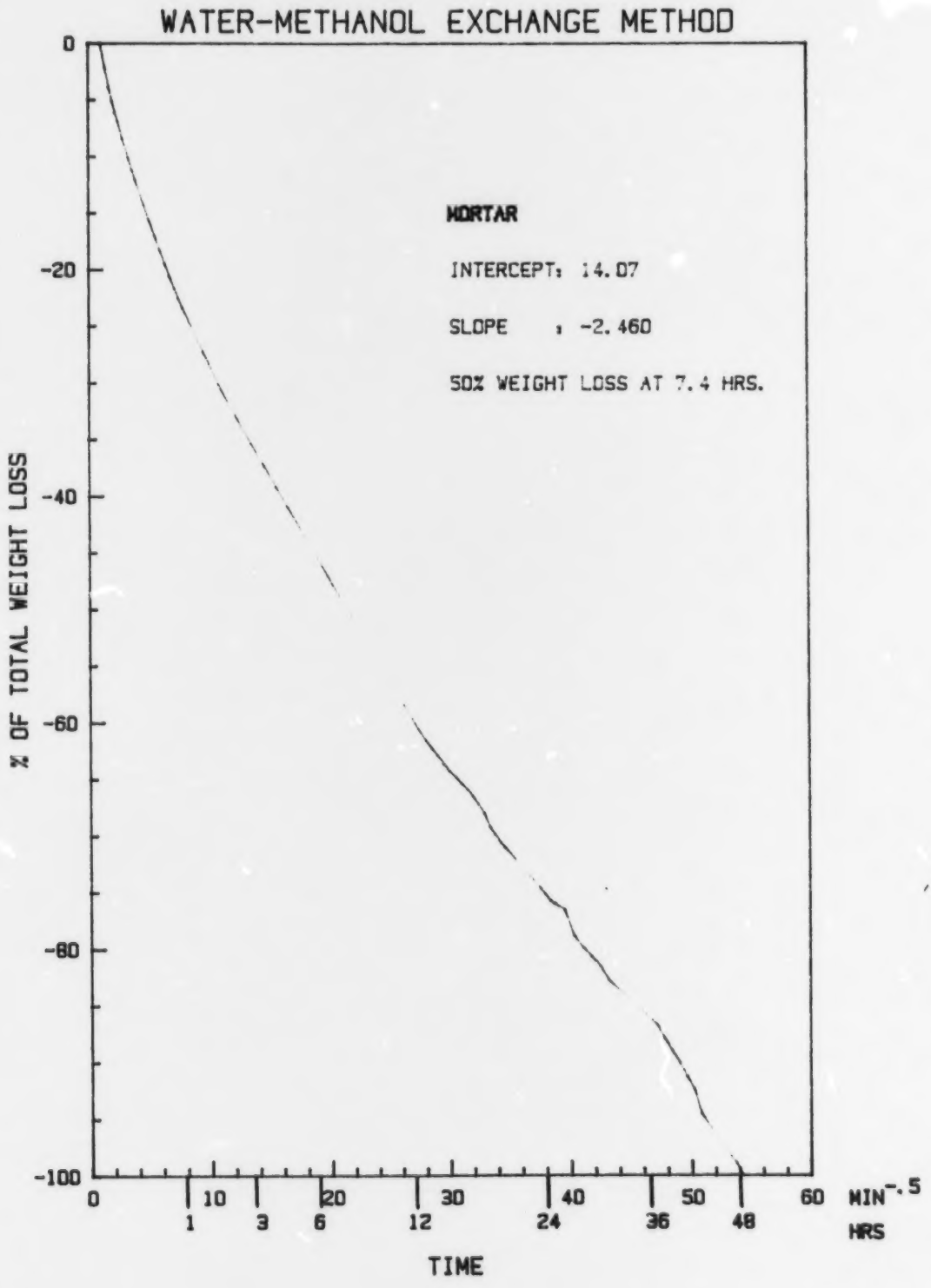


Appendix A-13



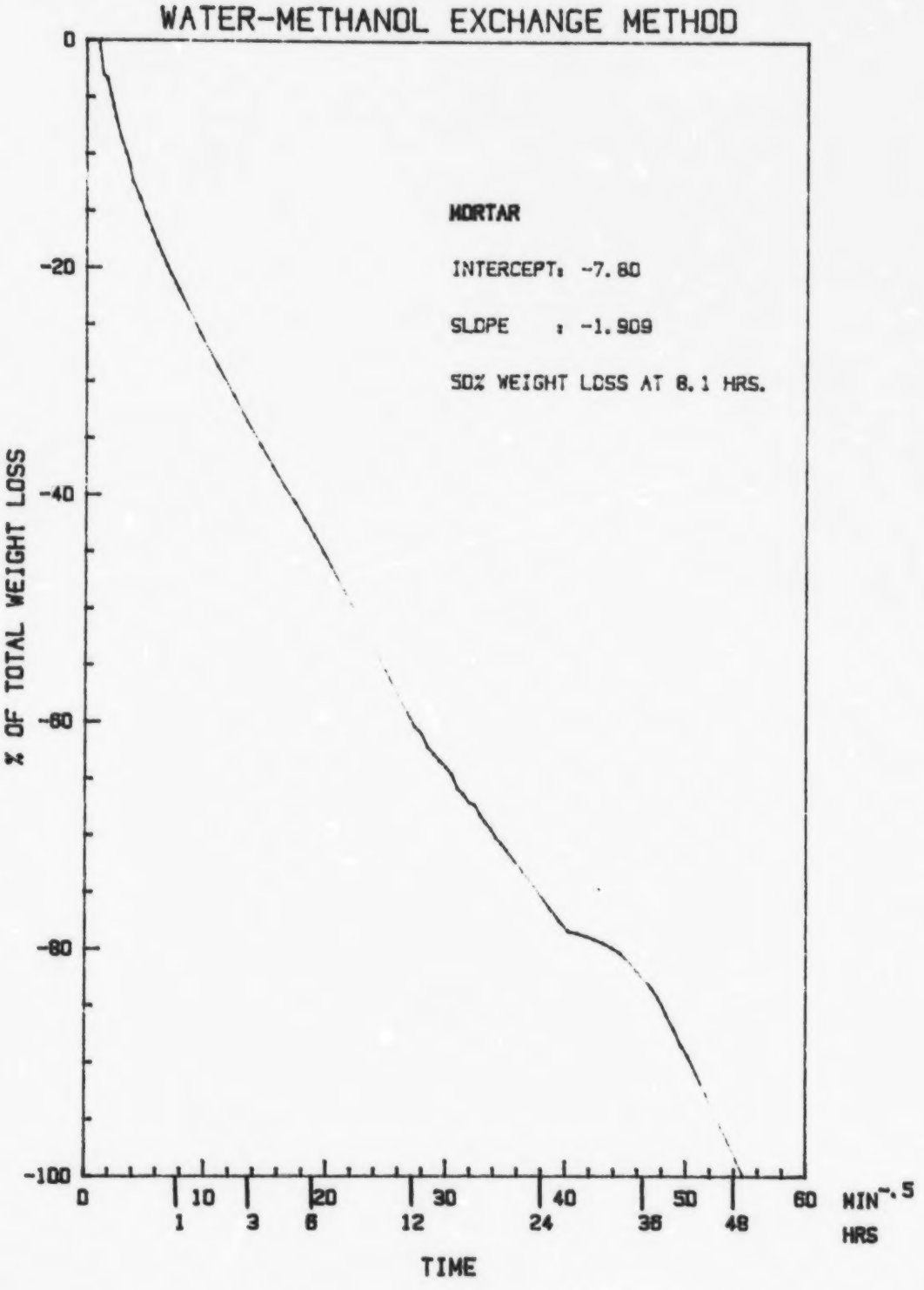
Appendix A-14

FLY ASH T 25% - RUN #1



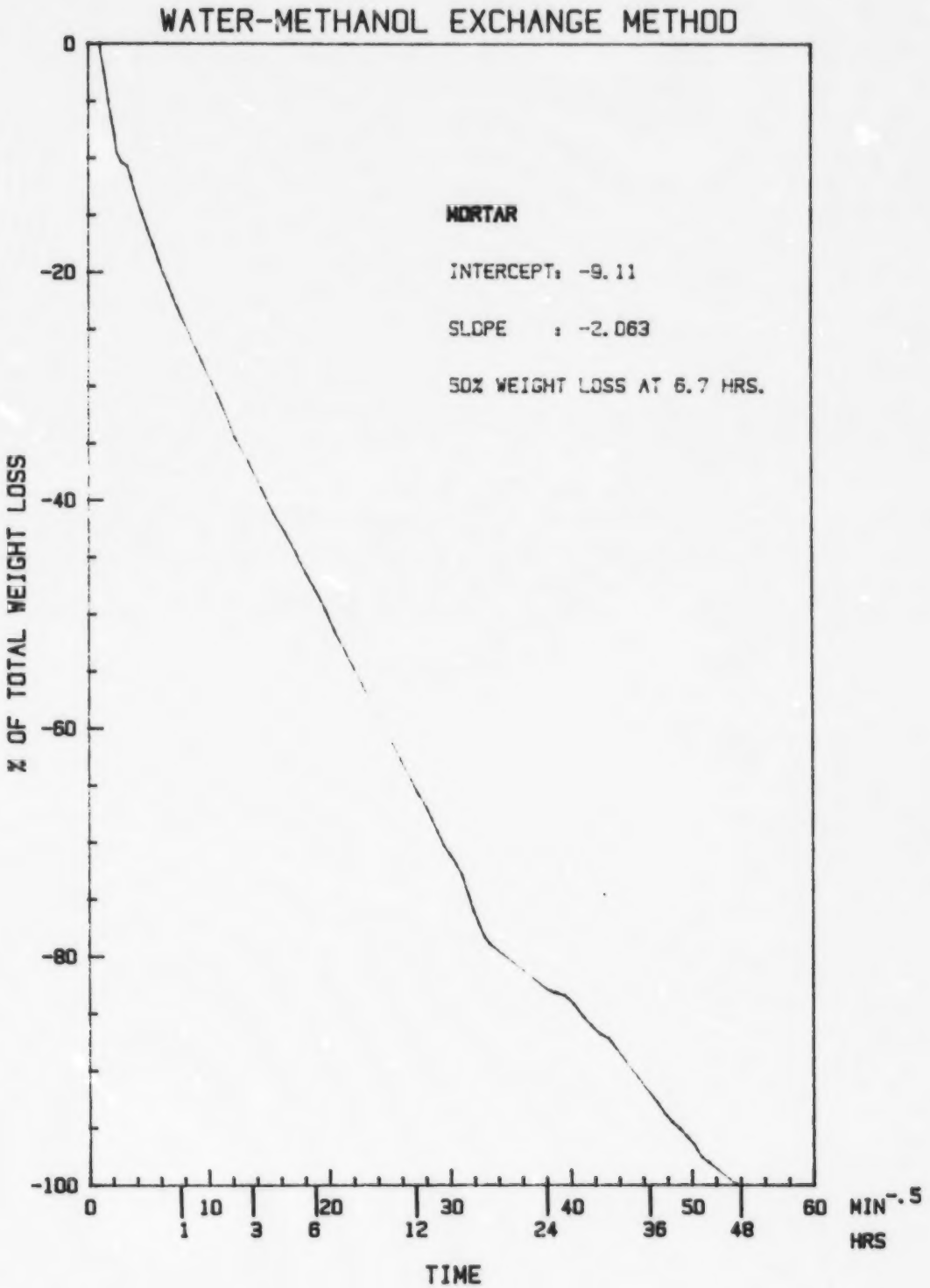
Appendix A-15

FLY ASH T 25% - RUN #2



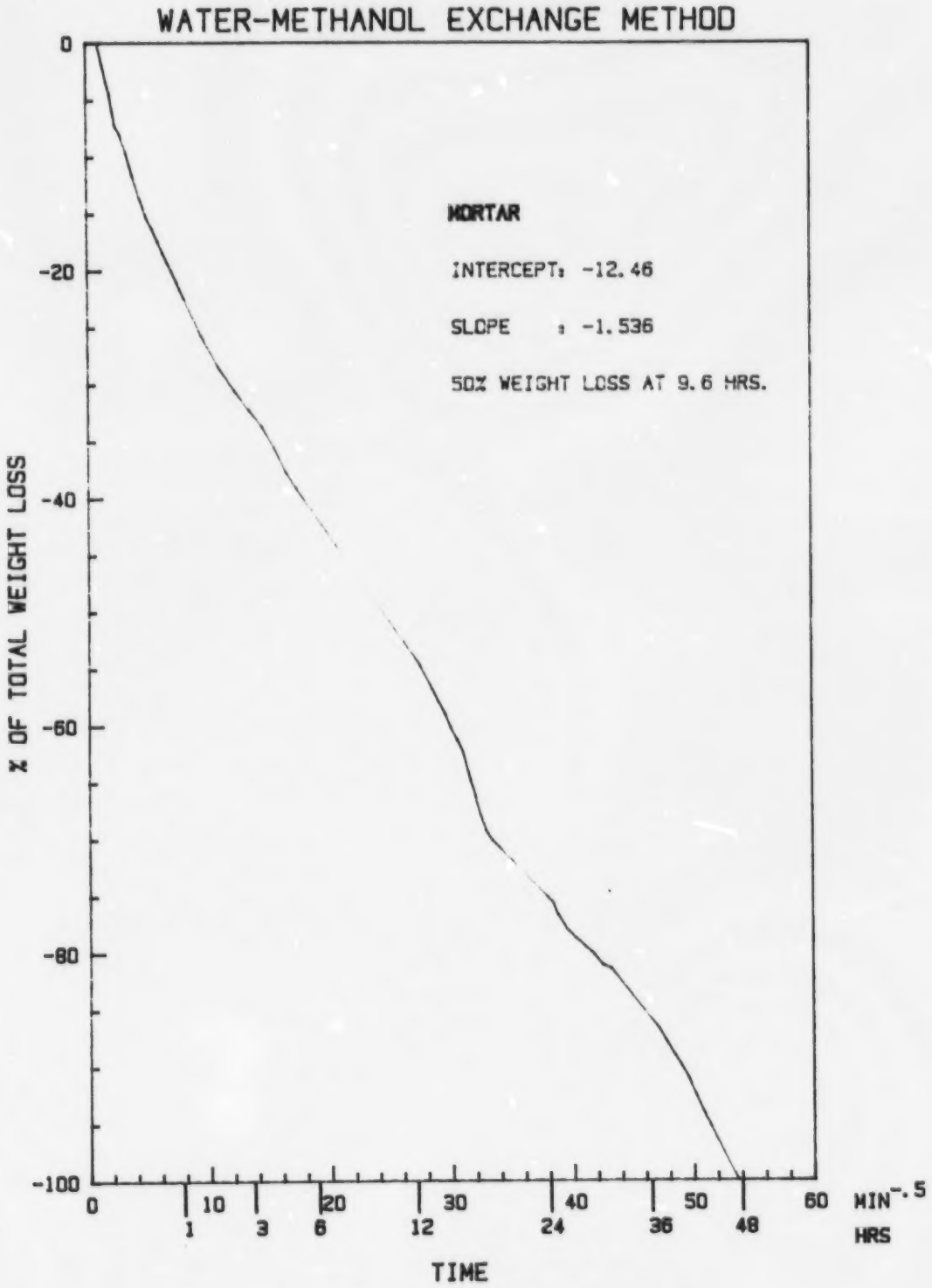
Appendix A-16

FLY ASH T 35% - RUN #1



Appendix A-17

FLY ASH T 35% - RUN #2



Appendix A-18

Appendix B-1
Fly Ash Characterization Data

	Trenton	Wabamum	Nanticoke	Grand Lake
SiO_2	42.66	59.02	50.44	39.63
Al_2O_3	23.68	21.96	22.35	12.74
TiO_2	0.86	0.63	1.01	0.60
P_2O_5	0.51	0.31	0.49	0.99
Fe_2O_3	23.38	3.13	10.50	39.87
T-CaO	2.67	10.63	6.02	2.90
SrO	nil	nil	nil	nil
MgO	1.23	1.77	0.92	0.82
Na_2O	0.56	0.30	0.56	0.10
K_2O	2.32	0.72	0.86	1.75
SO_3 *	0.96	0.16	0.52	0.75
Loss	0.70	0.70	6.89	0.75
Total	99.33	99.33	100.56	100.90
Total alkali (eq.Na_2O)	2.09	0.77	1.13	1.25
Density g/cm^3	2.60	2.22	2.32	2.93
Blaine cm^2/g	3260	2630	8250	1400
% Passing 325 mesh	86.1	60.1	64.9	77.4
Pozzolanic activity ≠ with cement - % @ 28-d	98	82	84	80
with lime - MPa @ 7-d	7.4	4.8	5.6	4.9

* Fly ash @ 750°C
≠ ASTM C311

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Trenton (N.S.) Fly Ash

Density 2.60 g/cc LIQUID A-13 Density 0.821 g/cc Viscosity 8.193 cp

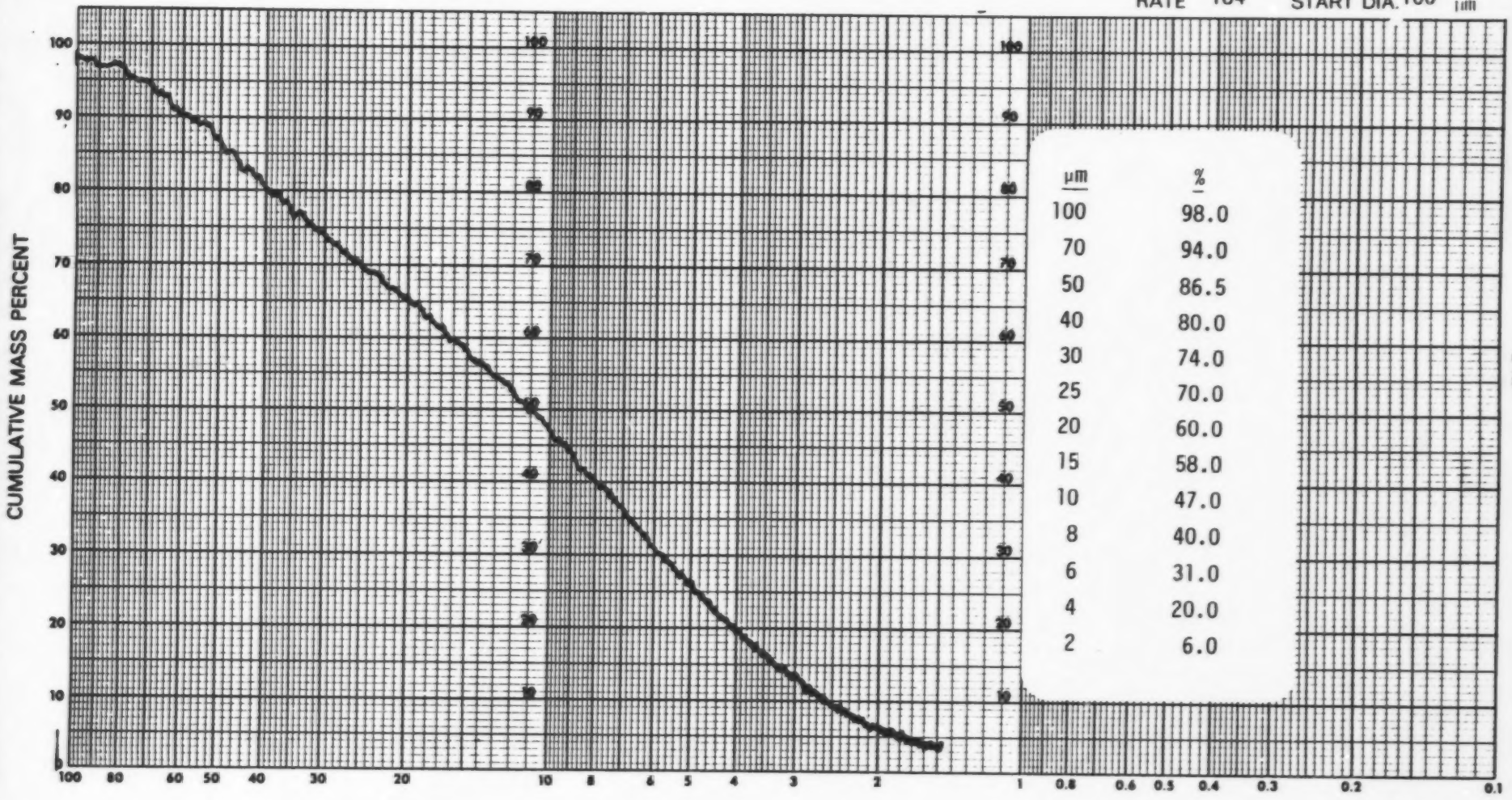
Preparation 2.3% Sample Removed with a 106 µm sieve

DATE November 22, 1984

BY R. Ferguson

TEMPERATURE 31 °C

RATE 184 START DIA. 100 µm



µm	%
100	98.0
70	94.0
50	86.5
40	80.0
30	74.0
25	70.0
20	60.0
15	58.0
10	47.0
8	40.0
6	31.0
4	20.0
2	6.0

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Appendix B-2

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Wabamun Fly Ash (Edmonton)

DATE November 23, 1984

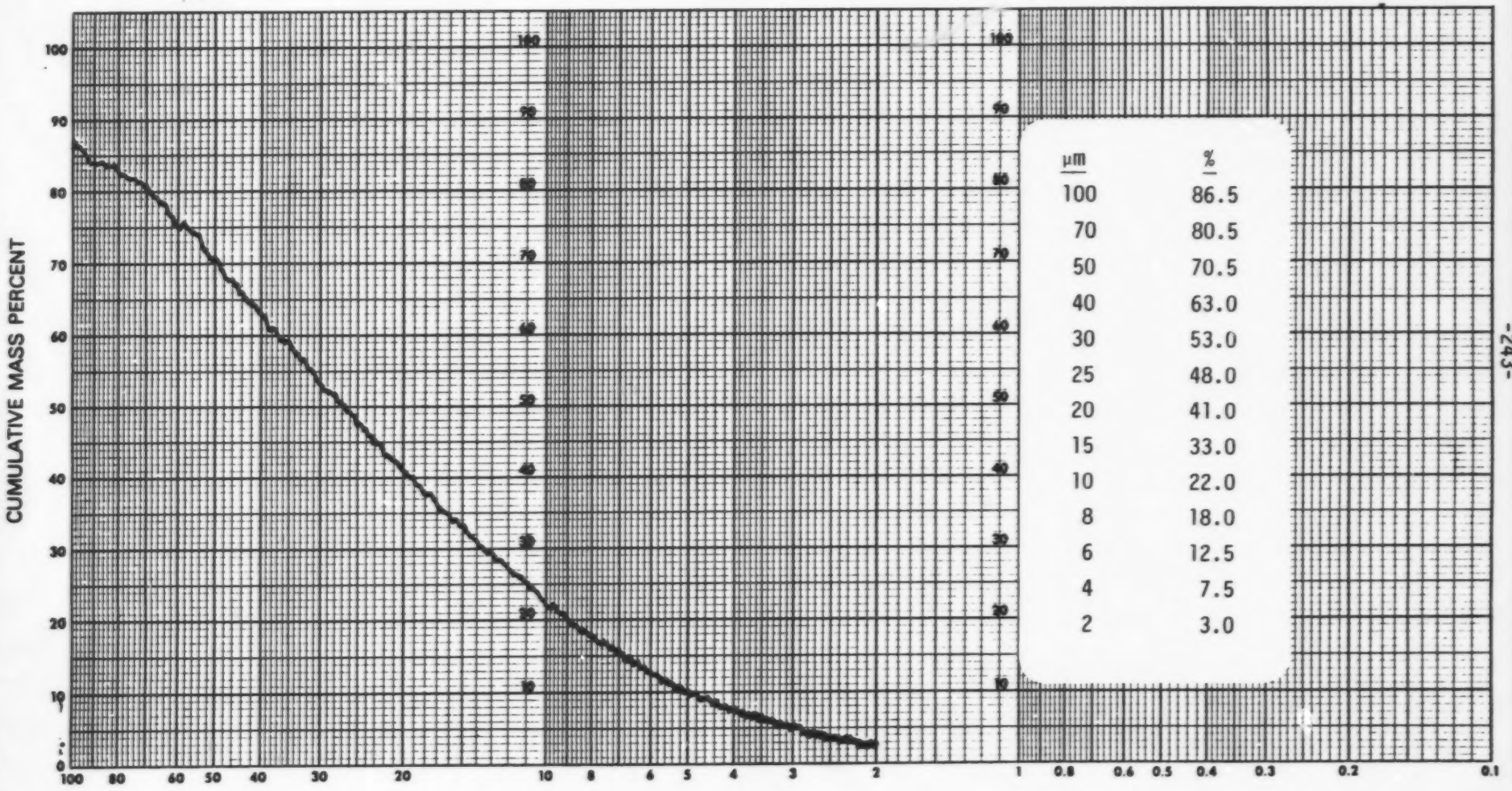
Density 2.22 g/cc LIQUID A-13 Density 0.822 g/cc Viscosity 8.463 cp

BY R. Ferguson

Preparation 13.9% Sample removed with a 106 µm sieve

TEMPERATURE 30 °C

RATE 140 START DIA. 100 µm



µm	%
100	86.5
70	80.5
50	70.5
40	63.0
30	53.0
25	48.0
20	41.0
15	33.0
10	22.0
8	18.0
6	12.5
4	7.5
2	3.0

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Appendix B-3

Form 500/42701

[redacted]AR[redacted]E S[redacted]IST[redacted]UTI[redacted]

SAMPLE IDENTIFICATION Nanticoke (Ontario) Fly Ash

Density 2.32 g/cc LIQUID A-13 Density 0.822 g/cc Viscosity 8.463 cp

Preparation 12.7% Sample Removed with a 106 µm sieve

DATE November 23, 1984

BY R. Ferguson

TEMPERATURE 30 °C

RATE 150 START DIA. 100 µm

µm	%
100	87.0
70	84.0
50	77.0
40	69.5
30	60.5
25	55.0
20	48.0
15	39.0
10	27.0
8	21.5
6	15.0
4	8.5
2	3.0

CUMULATIVE MASS PERCENT

EQUIVALENT SPHERICAL DIAMETER, µm

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Appendix B-4

PARTICLE SIZE DISTRIBUTION

SAMPLE IDENTIFICATION Grand Lake (N.B.) Fly Ash

DATE November 23, 1984

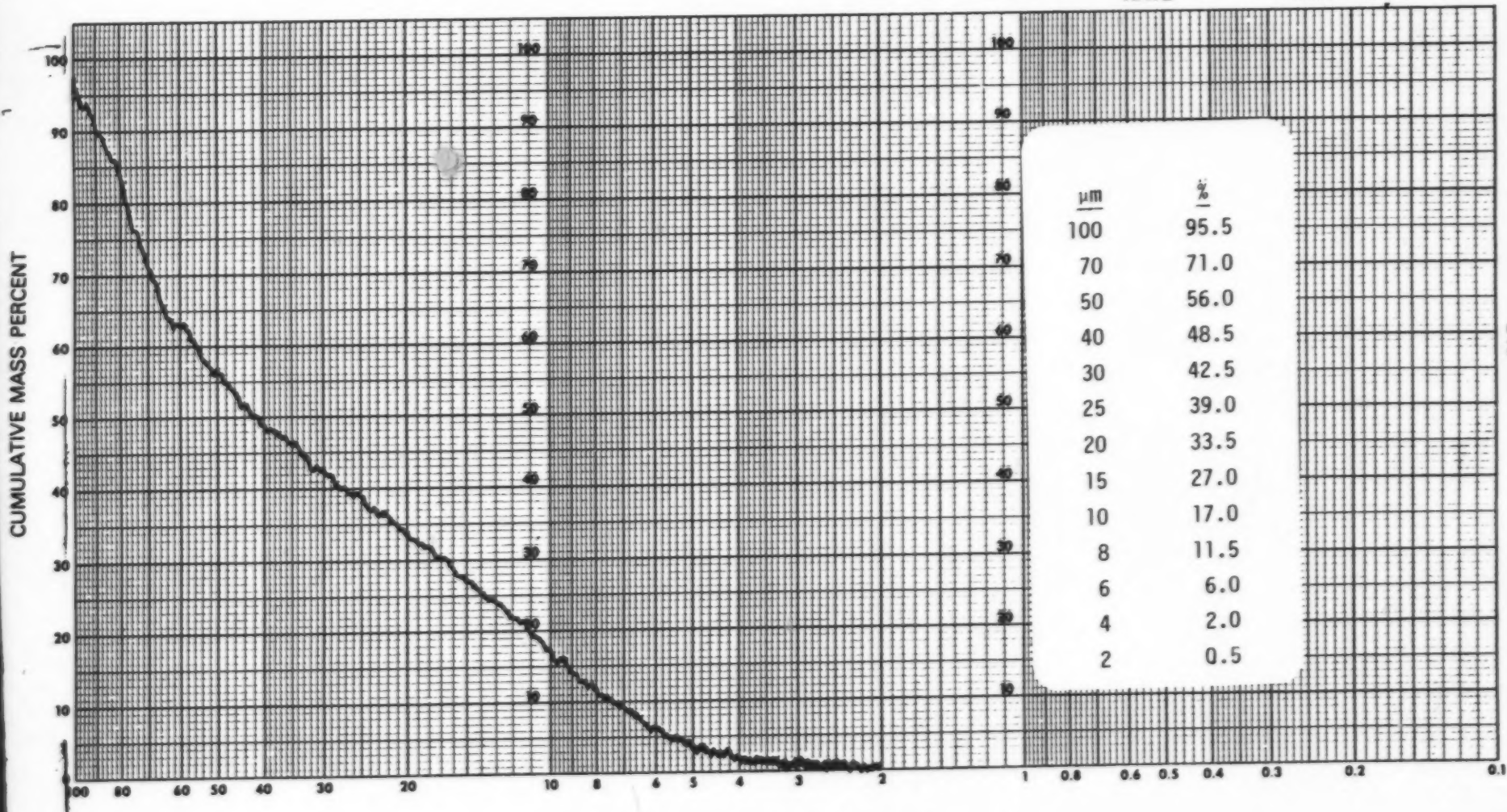
Density 2.93 g/cc LIQUID A-13 Density 0.822 g/cc Viscosity 8.463 cp

BY R. Ferguson

Preparation 4.3% Sample Removed with a 106 µm sieve

TEMPERATURE 30 °C

RATE 211 START DIA. 100 µm



µm	%
100	95.5
70	71.0
50	56.0
40	48.5
30	42.5
25	39.0
20	33.5
15	27.0
10	17.0
8	11.5
6	6.0
4	2.0
2	0.5

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Appendix B-5